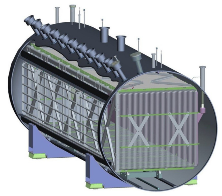
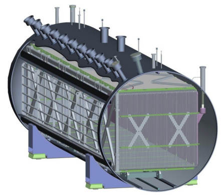


Space Charge Effect at MicroBooNE

Michael Mooney

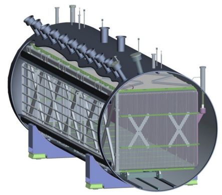
The experiment formerly known as LBNE – BNL Meeting

February 11th, 2015

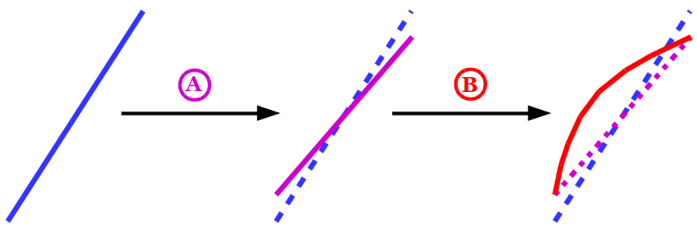


Introduction

- BNL has developed a tool to study space charge effect at the MicroBooNE detector
  - **SpaCE** – Space Charge Estimator
  - Study **simple problems** first in detail with dedicated simulations
  - Maintain complete control over simulation chain for now – no LArSoft, no ANSYS, **only code we develop** (thus fully understand)
  - Eventually can network with LArSoft to extract correction factors from calibration and to simulate effect in MC
- Outline:
  - Brief review of Space Charge Effect (SCE)
  - Overview of SpaCE
  - **Simulation** of effect on physics object reconstruction
  - Proposal of **calibration** scheme using laser tracks + cosmic muons

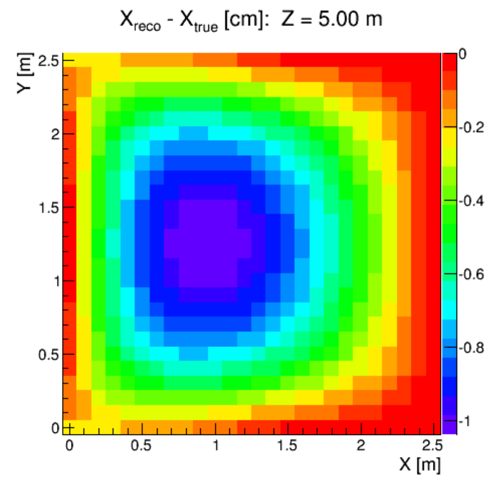


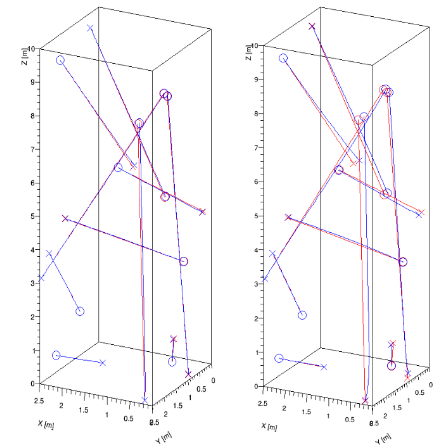
Roadmap of Today's Talk



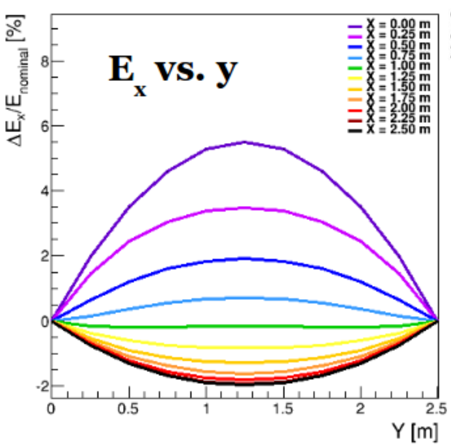
1. Review of Space Charge Effect

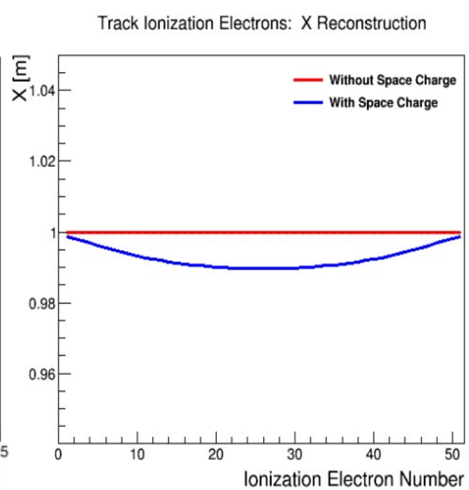
2. Overview of SpaCE Code Suite

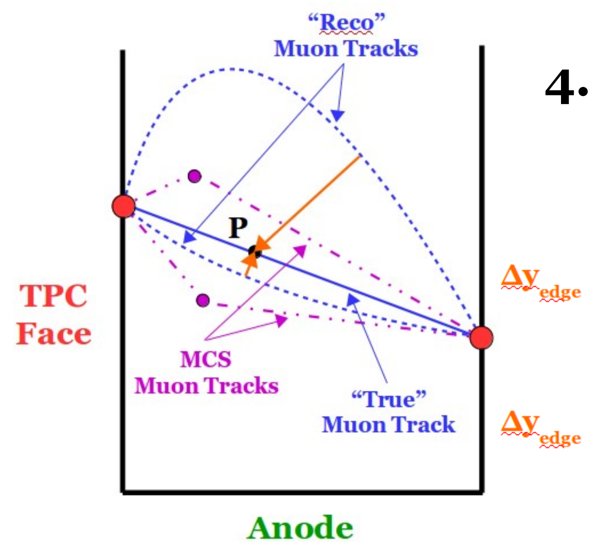




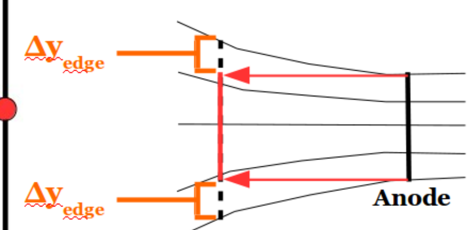
3. Simulation of SCE

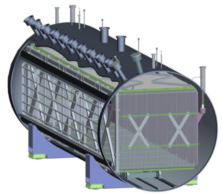






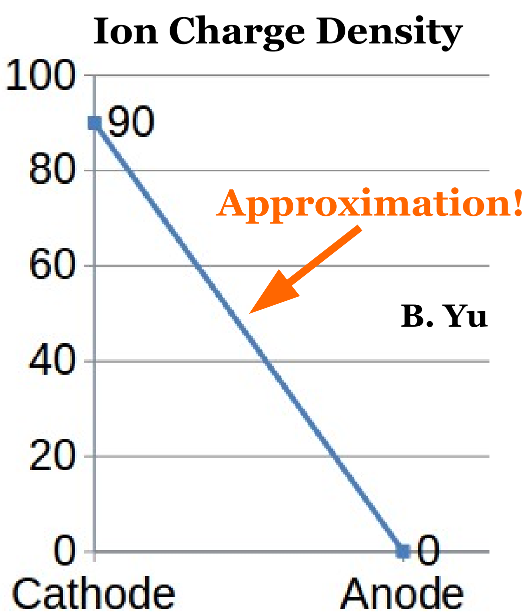
4. Calibration Scheme

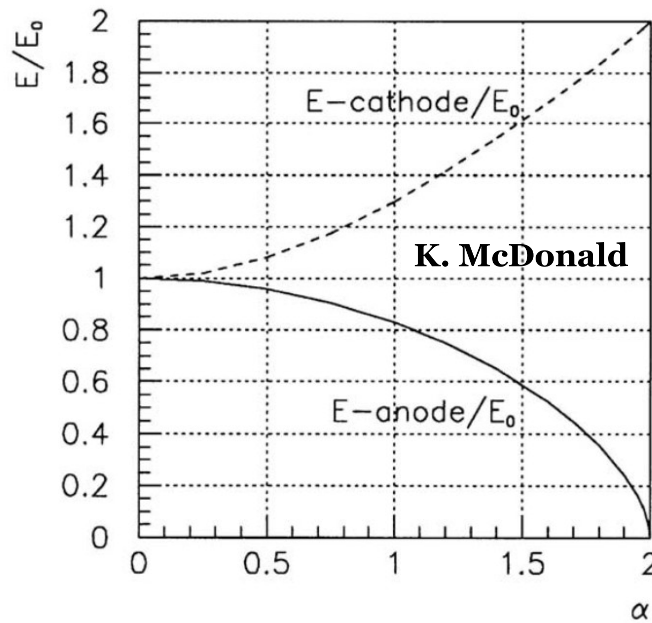




Space Charge Effect

- **Space charge**: excess electric **charge** (slow-moving ions) distributed over region of **space** due to cosmic muons passing through the liquid argon
  - Modifies E field in TPC, thus track/shower reconstruction
  - For LAr neutrino experiments, effect **worst** at MicroBooNE

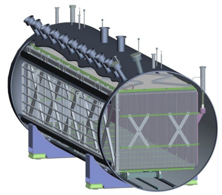




$$\alpha = \frac{D}{E_0}\sqrt{\frac{K}{\epsilon\mu}}$$

$$\mathbf{v} = \mu\mathbf{E}$$

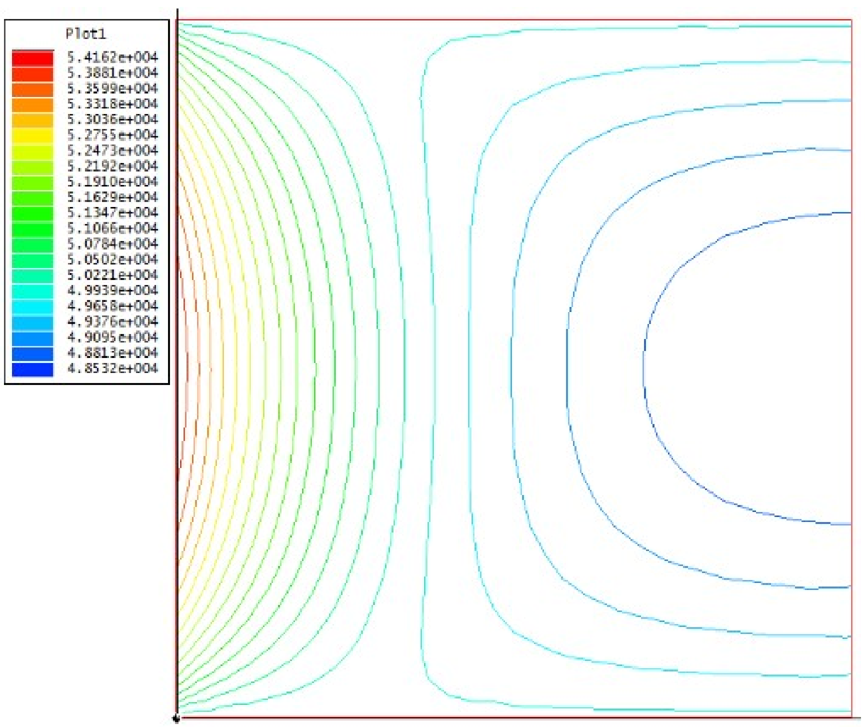
No Drift!



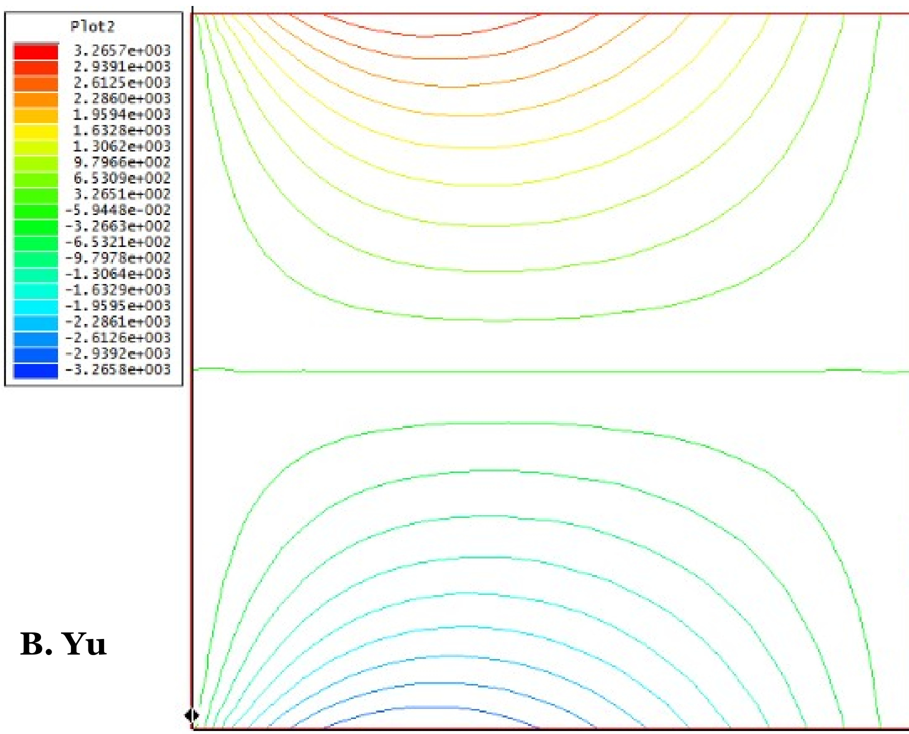
Impact on E Field

- Visualization of impact on E field (Bo Yu's Maxwell-2D studies)
- Assumptions:
  - Constant charge deposition rate throughout detector
  - No liquid argon flow – **serious complication**

Drift Direction



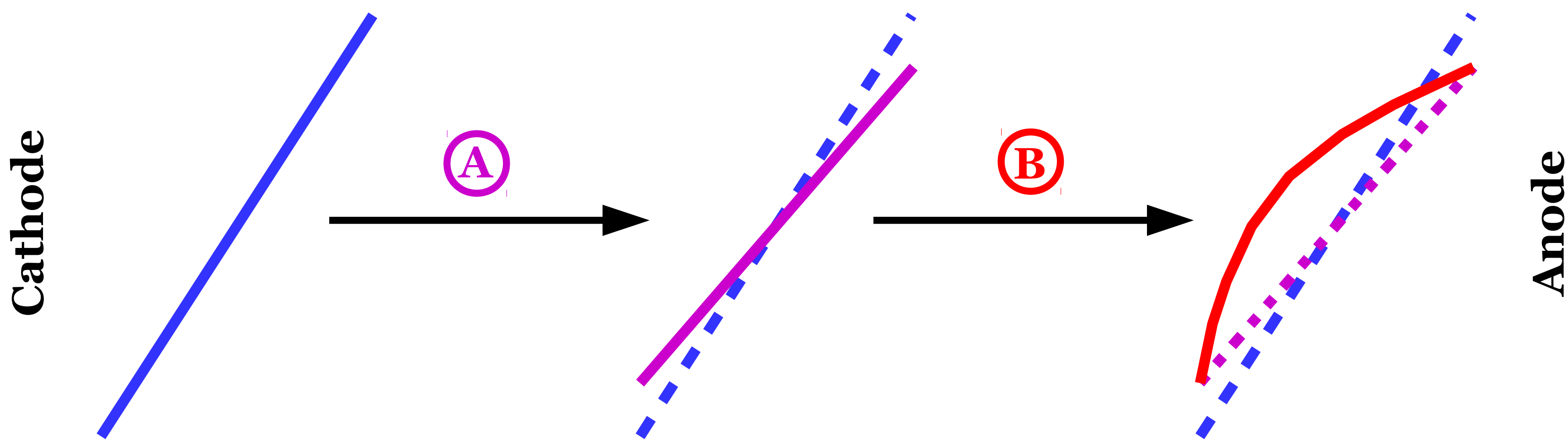
Lateral Directions

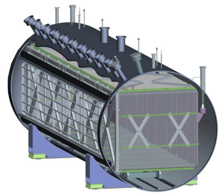


B. Yu

Impact on Track Reco.

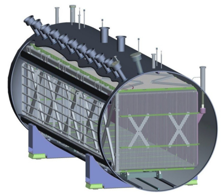
- Two separate effects on reconstructed **tracks**:
  - Ⓐ • Reconstructed track shortens laterally (looks rotated)
  - Ⓑ • Reconstructed track bows toward cathode (greater effect near center of detector)
- Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven calibration





SpaCE: Overview

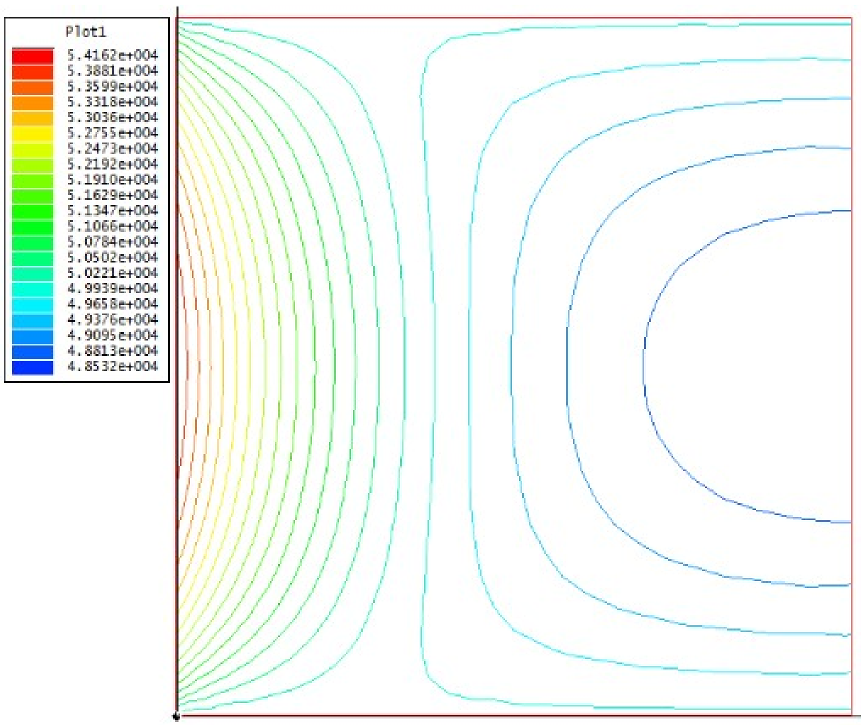
- Code written in C++ with ROOT libraries
- Also makes use of external libraries (ALGLIB)
- Primary features:
  - Obtain E fields analytically (on 3D grid) via **Fourier series**
  - Use **interpolation** scheme (RBF – radial basis functions) to obtain E fields in between solution points on grid
  - Generate tracks in volume – line of uniformly-spaced points
  - Employ **ray-tracing** to “read out” reconstructed {x,y,z} point for each track point – RKF45 method
- First implemented effects of uniform space charge deposition without liquid argon flow (only linear space charge density)
  - Recently: solved for **arbitrary space charge configuration**
    - Can now model effects of liquid argon flow!

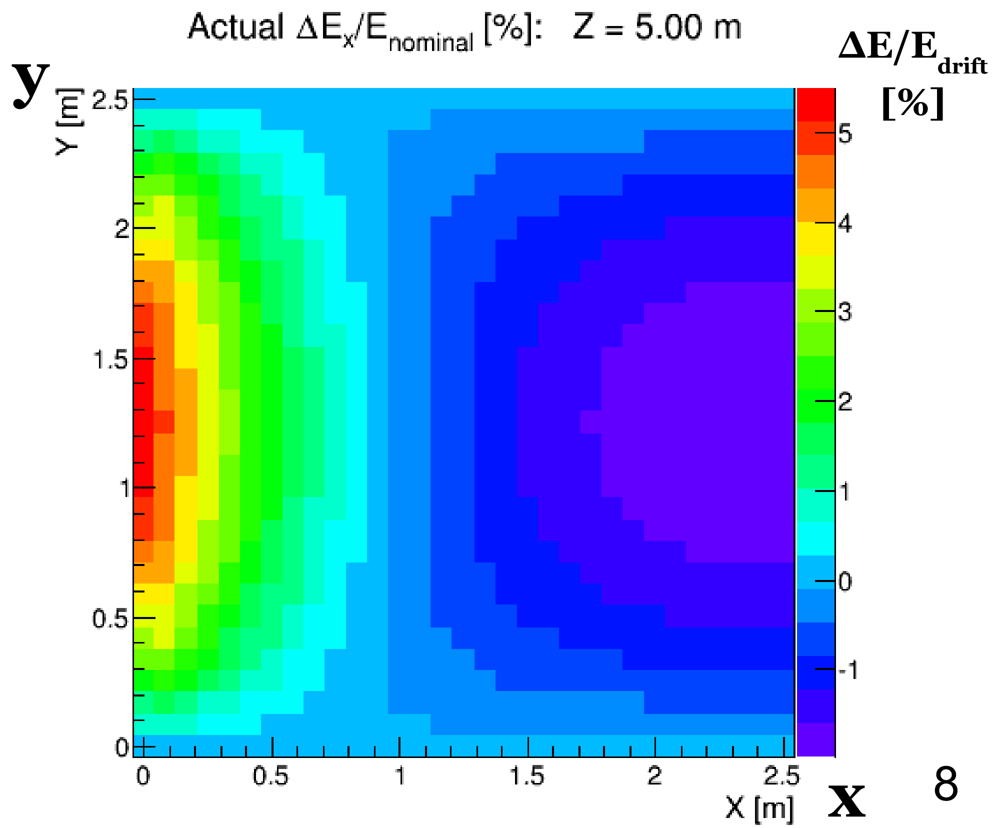


Compare to FE Results: E_x

BROOKHAVEN NATIONAL LABORATORY

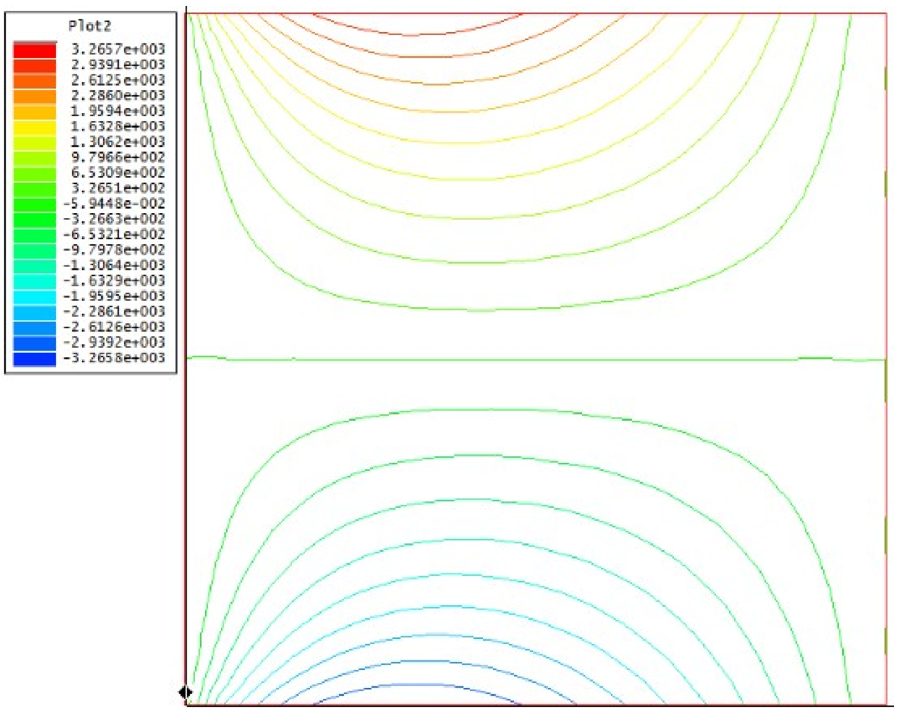
- Looking at central z slice (z = 5 m) in x-y plane
- Very good shape agreement compared toBo's 2D FE (Finite Element) studies
- Normalization differences understood (using different rate)

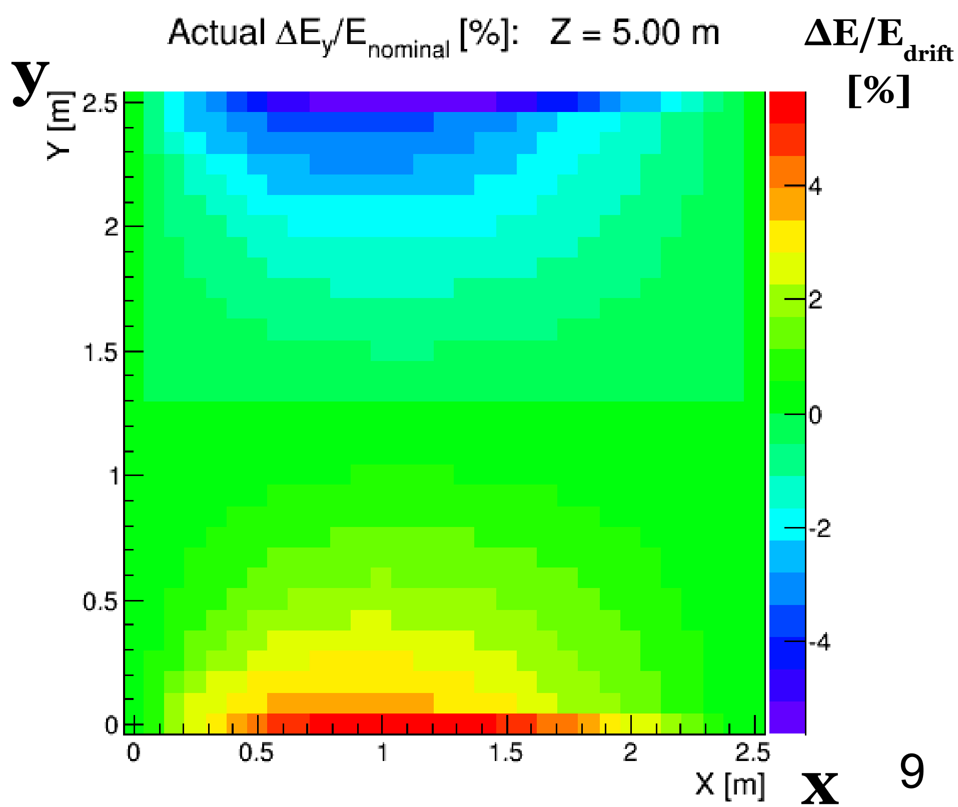




Compare to FE Results: E_y

- Looking at central z slice (z = 5 m) in x-y plane
- Very good shape agreement here as well
  - Parity flip due to difference in definition of coordinate system

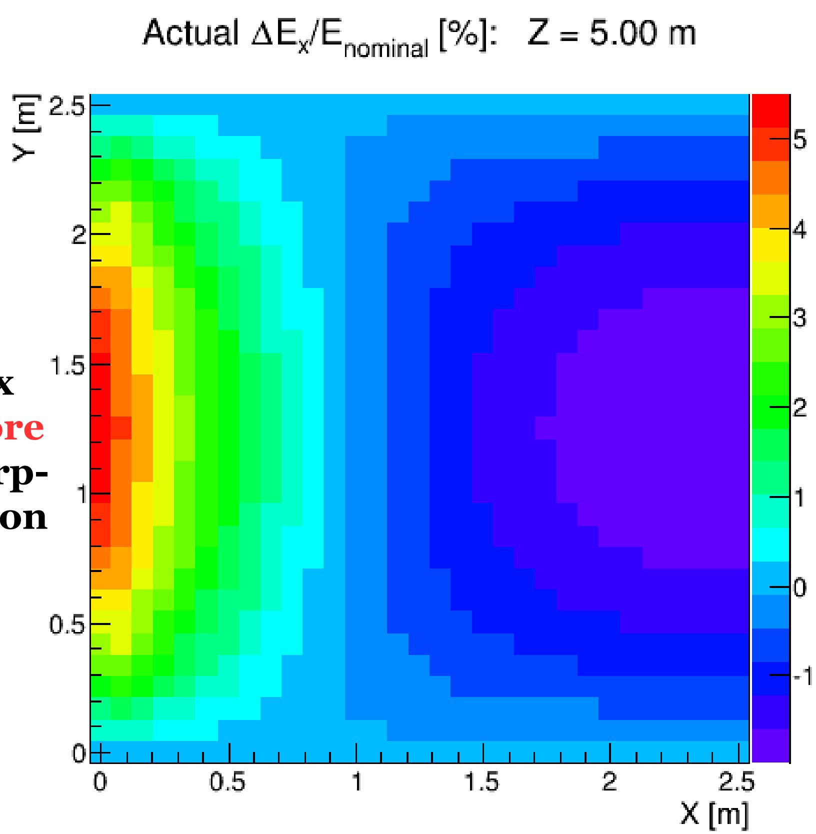


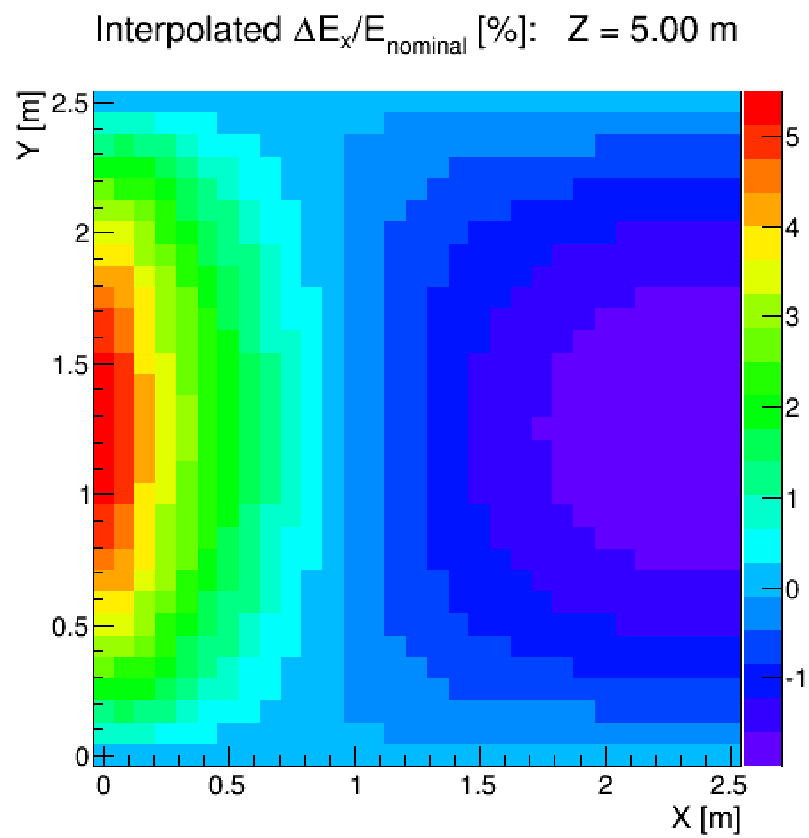


E Field Interpolation

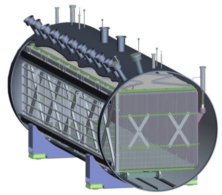
- Compare 30 x 30 x 120 field calculation (left) to 15 x 15 x 60 field calculation with interpolation (right)
- Include analytical continuation of solution points **beyond** boundaries in model – improves performance near edges

E_x
Before
Interp-olation



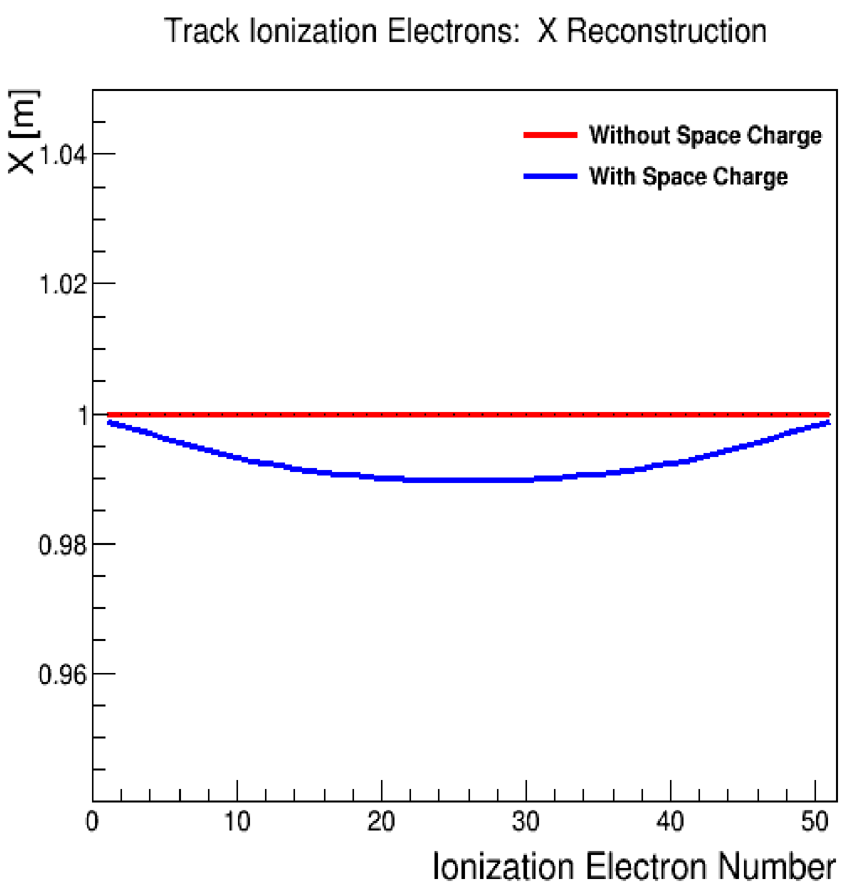


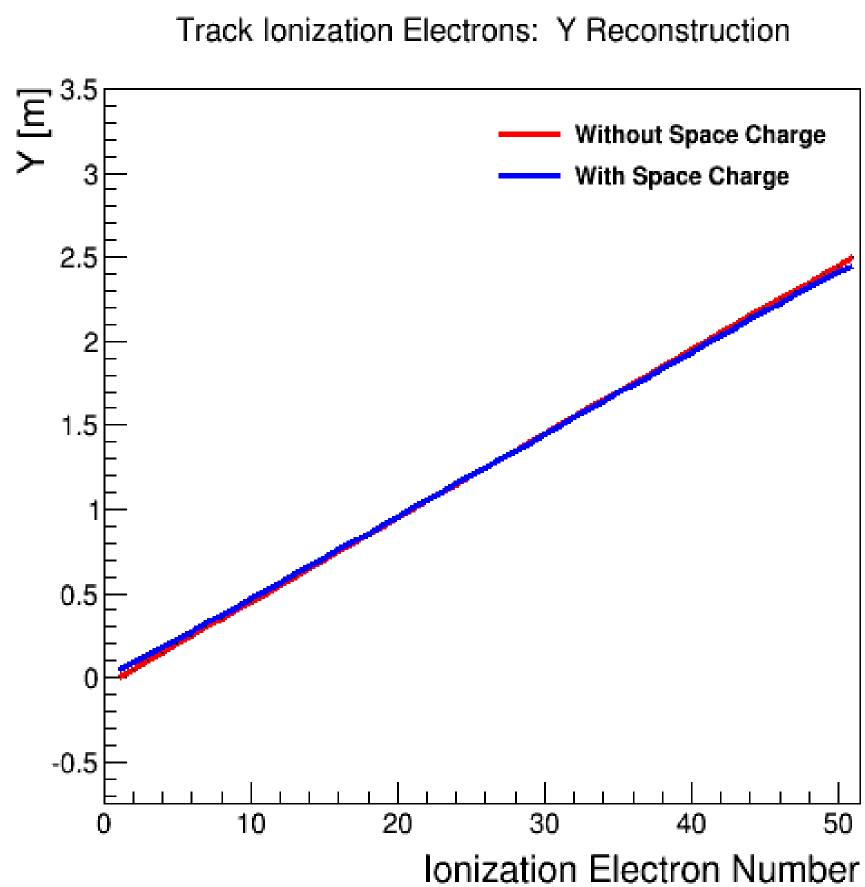
E_x
After
Interp-olation

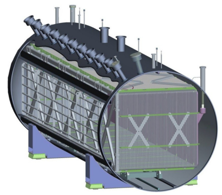


Ray-Tracing

- Example: track placed at **x = 1 m** (anode at x = 2.5 m)
  - z = 5 m, y = [0,2.5] m



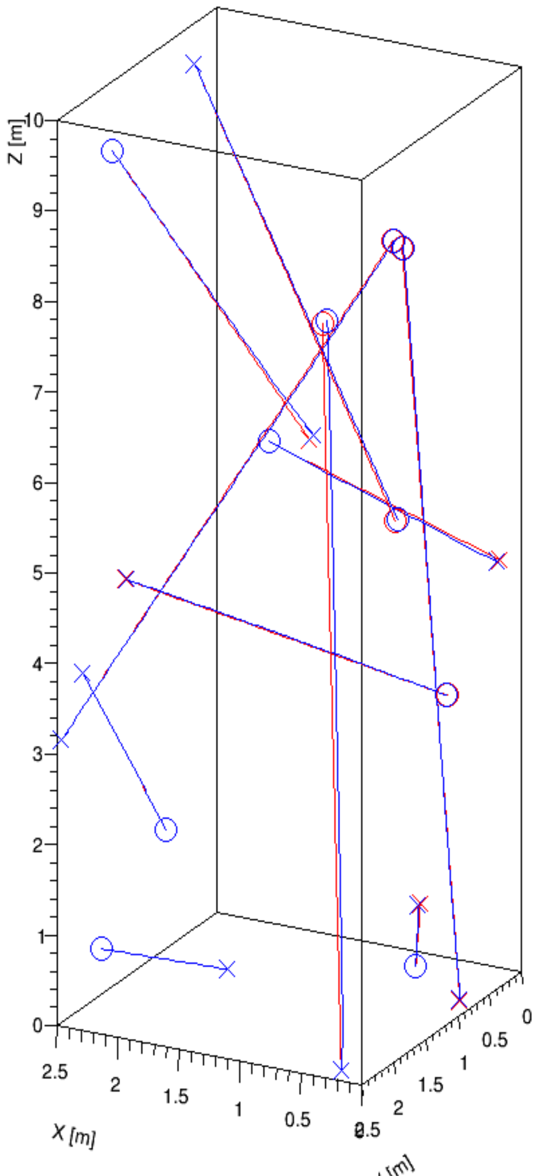


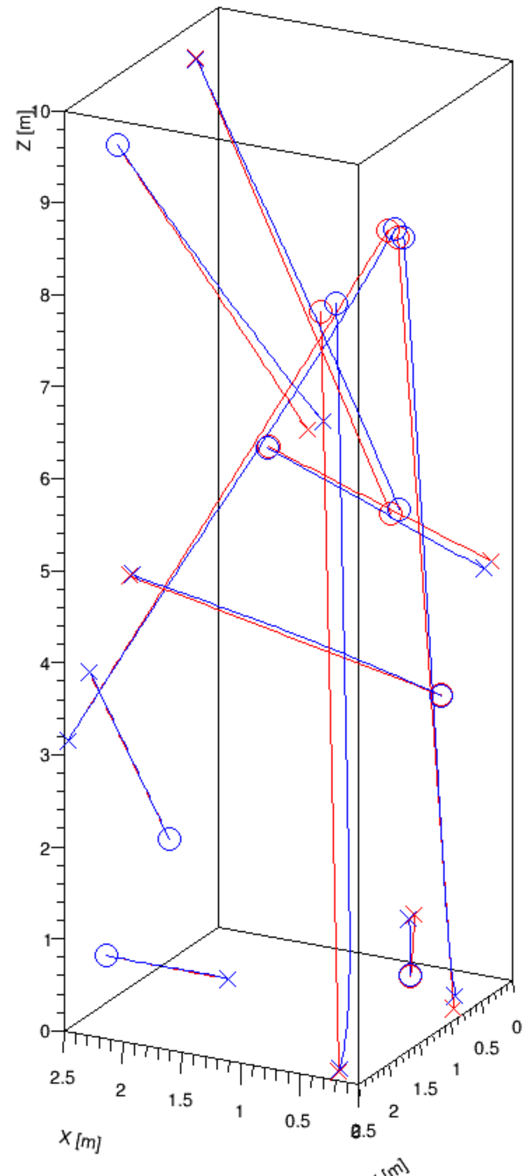


Sample "Cosmic Event"

Nominal Drift Field

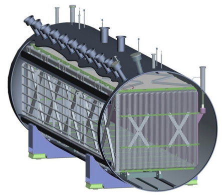
500 V/cm





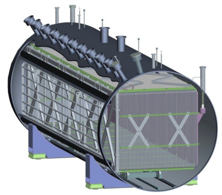
Half Drift Field

250 V/cm



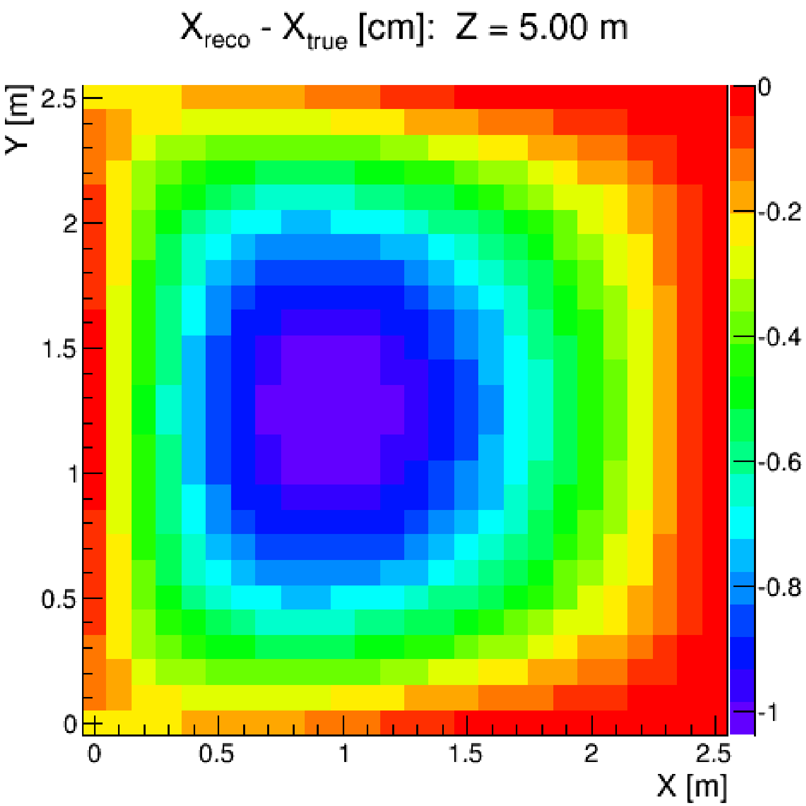
Simulation of SC Effect

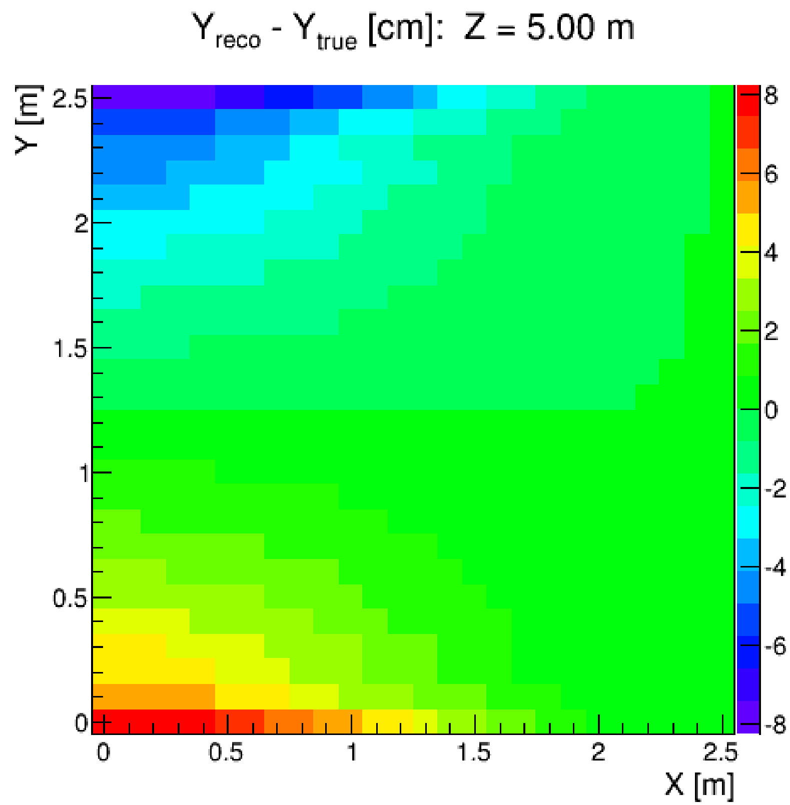
- Can use SpaCE to produce displacement maps
  - **Forward transportation**: $\{x, y, z\}_{\mathbf{true}} \rightarrow \{x, y, z\}_{\mathbf{reco}}$
    - Use to **simulate** effect in MC
    - Uncertainties describe accuracy of simulation
  - **Backward transportation**: $\{x, y, z\}_{\mathbf{reco}} \rightarrow \{x, y, z\}_{\mathbf{true}}$
    - Derive from **calibration** and use in data or MC to correct reconstruction bias
    - Uncertainties describe remainder systematic after bias-correction
- Two principal methods to encode displacement maps:
  - **Matrix representation** – more generic/flexible
  - **Parametric** representation (for now, $5^{th}/7^{th}$ order polynomials) – fewer parameters
    - Uses matrix representation as input



Simulation: Matrix Rep.

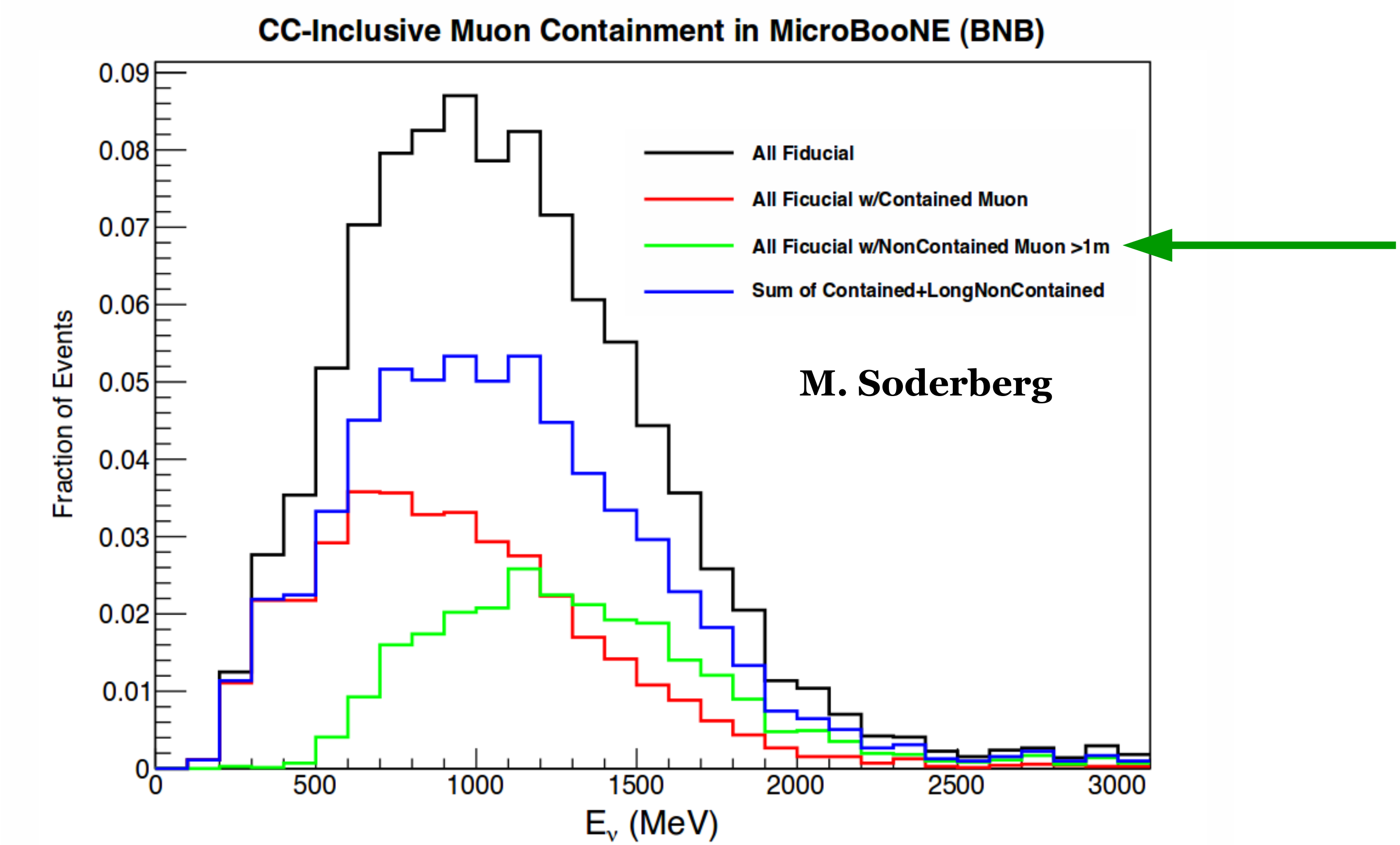
- Below: example of **forward transportation** for central z slice
- Can use interpolation methods to go to finer scales
- Can similarly produce backward transportation maps with same information and using interpolation methods



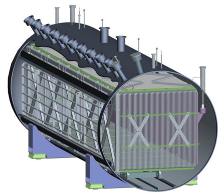


Physics Impact of SCE

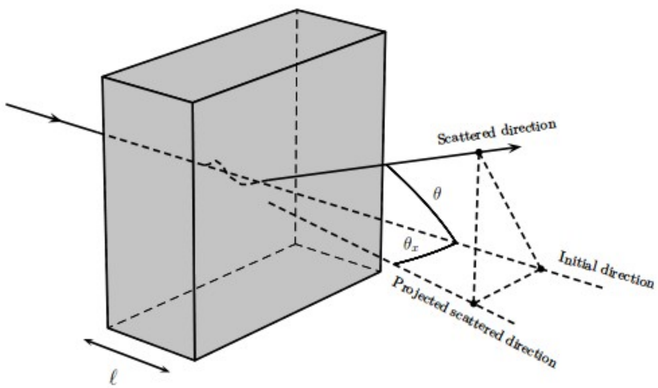
- A significant fraction of the CCQE muons will not be fully-contained within the detector… how to measure $\mathbf{p}_{\mathbf{track}}$?



Contained = 37%, Long (>1m) Non-Contained = 27%



Using MCS to Measure p_{track}



Idea: **RMS of Δθ distribution → p_{track} (“p_{RECO}”)**

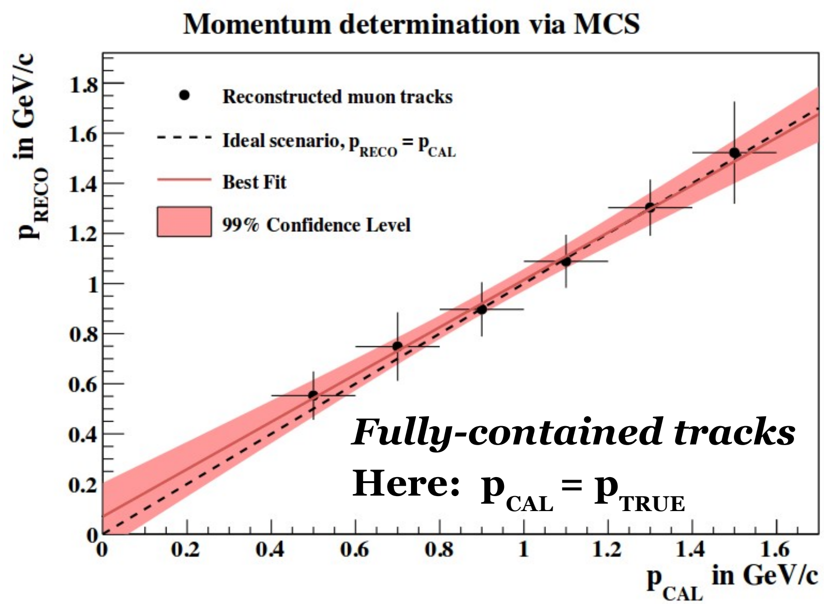
Small angle deflections are governed by the so-called modified Highland formula

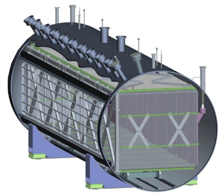
$$\theta_0 = \frac{13.6}{p\beta c}\sqrt{\frac{\ell}{X_0}}\left[1 + 0.0038\ \ell n\left(\frac{\ell}{X_0}\right)\right]$$

θ_0 : RMS of the Δθ distribution (mrad)
p : particle momentum (GeV/c)
\ell : material thickness
X_0 : radiation length

L. Kalousis

- Use angular deflections of track due to Multiple Coulomb Scattering (MCS) in order to find $\mathbf{p_{track}}$
- Need to see how SCE impacts this measurement!

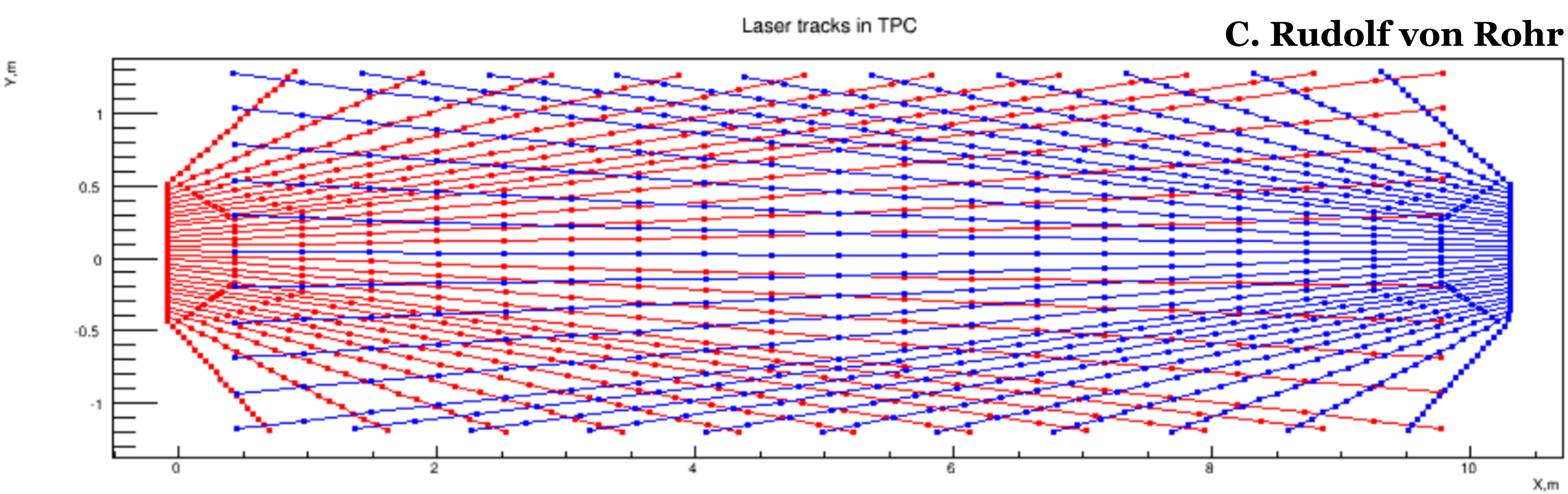


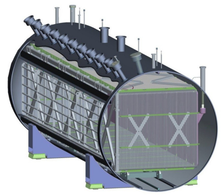


Laser Track Calibrations

- ♦ Can use laser system to calibrate out space charge effect
  - True laser track + reconstructed track → measure **backward transportation** displacement map
  - Evaluating performance of proposed laser track correction algorithms
- ♦ Complications:
  - Can't address time-dependencies of LAr flow, if non-negligible
  - Laser system **can only target part of TPC**

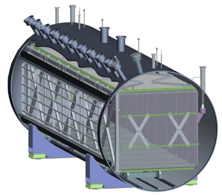
C. Rudolf von Rohr



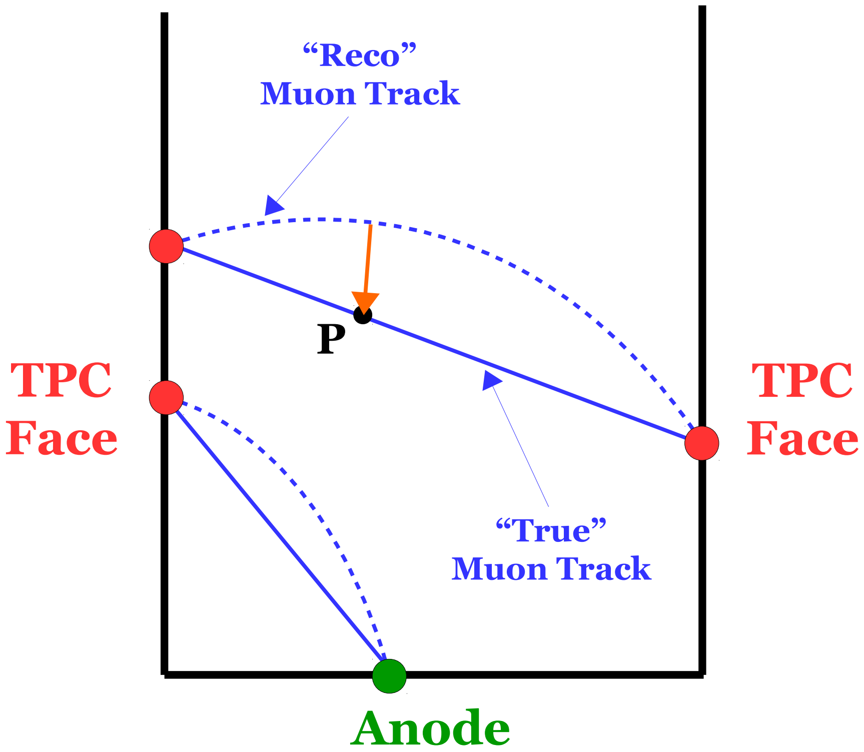


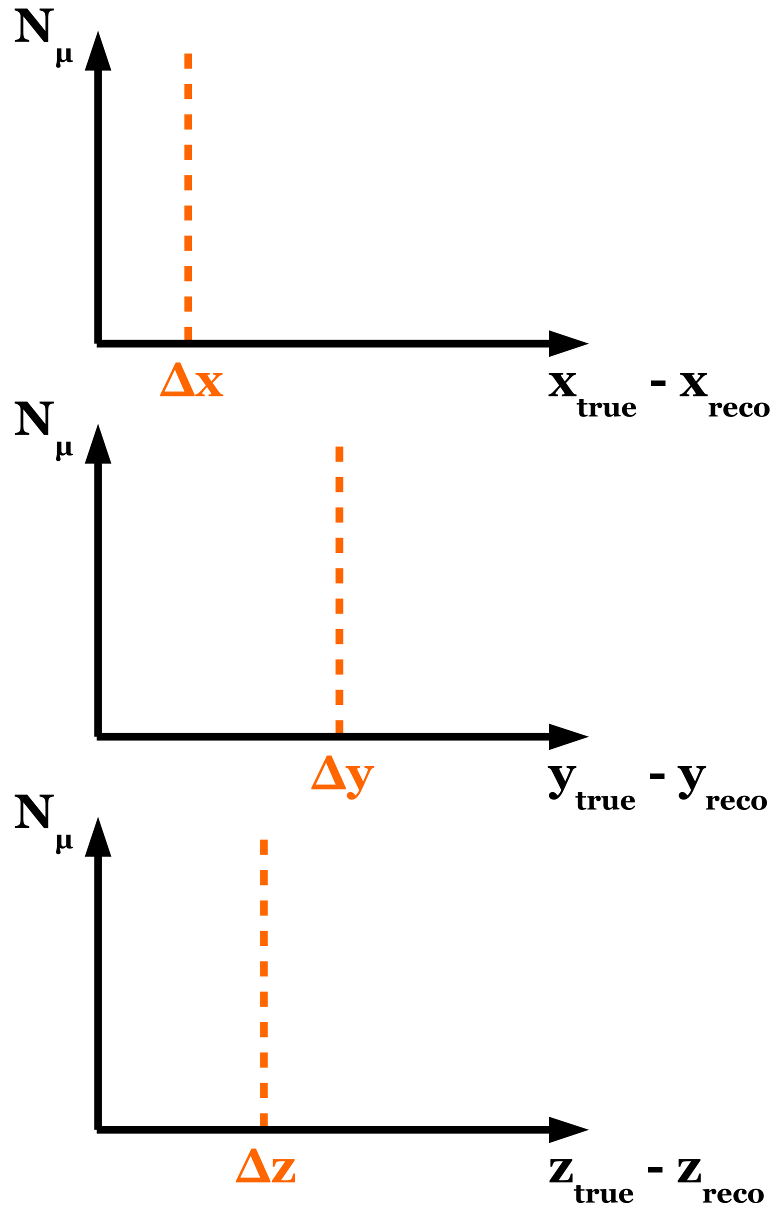
Calibration Scheme: SCT

- <u>Proposal</u>: fill in backward transportation displacement maps (where laser system can't reach) using **tomography** technique involving cosmic muons
- Algorithm: **Space Charge Tomography (SCT)**
- Main concepts:
  - First use laser crossings to unambiguously calibrate points in TPC bulk – **"X"**
  - Then use single laser tracks to calibrate points in bulk and on detector faces (the latter unambiguously) – **"L"**
  - Next use ensembles of cosmic muons passing through either anode and one other TPC face (near laser-calibrated point) or two non-anode TPC faces (near laser-calibrated points) – **"μ"**
    - No displacement at anode plane; know cosmic muon t_o from PMT system
    - Use median $\{\Delta x, \Delta y, \Delta z\}$ correction: **multiple-scattering averages out**
  - **Iterate**: $\mathbf{X \rightarrow L \rightarrow \overline{\mu} \rightarrow L \rightarrow \overline{\mu} \rightarrow L \rightarrow \ldots}$ (with $\mathbf{\overline{\mu} = \mu \rightarrow \mu \rightarrow \mu \rightarrow \ldots}$)
    - Use crossings of different muon paths ($\mathbf{\mu}$) within $\mathbf{\overline{\mu}}$ iteration (like **X**)



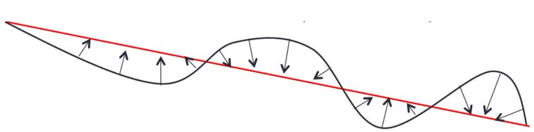
SCT "μ" Step: no MCS

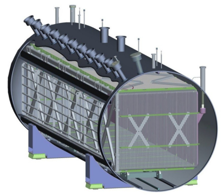




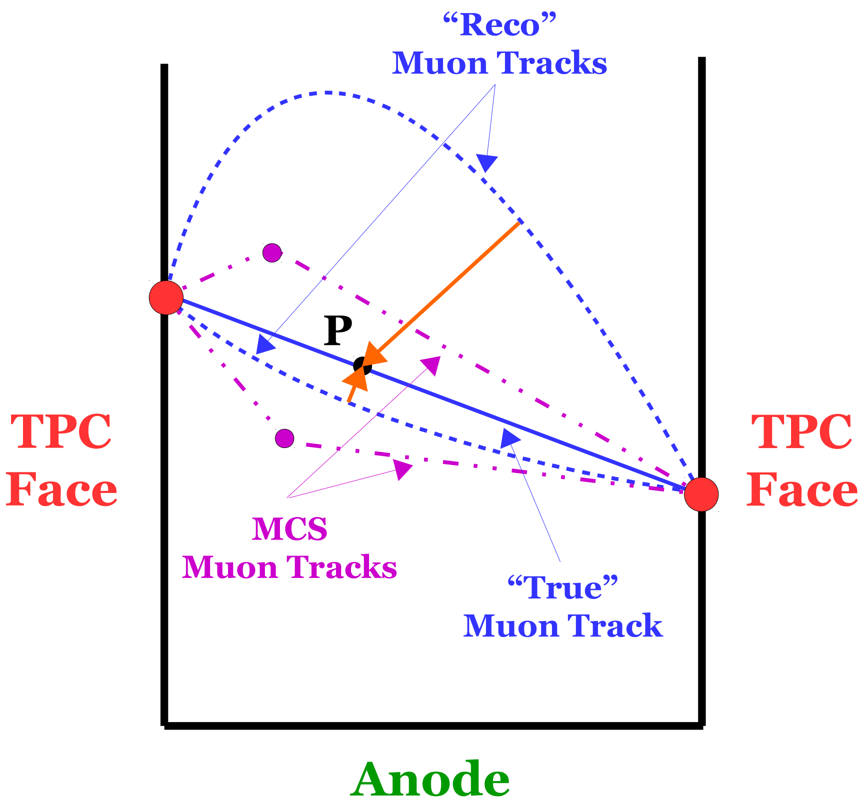
Correction to Point P:
{Δx, Δy, Δz}

Assumes perfect laser-track alg. (Bern)



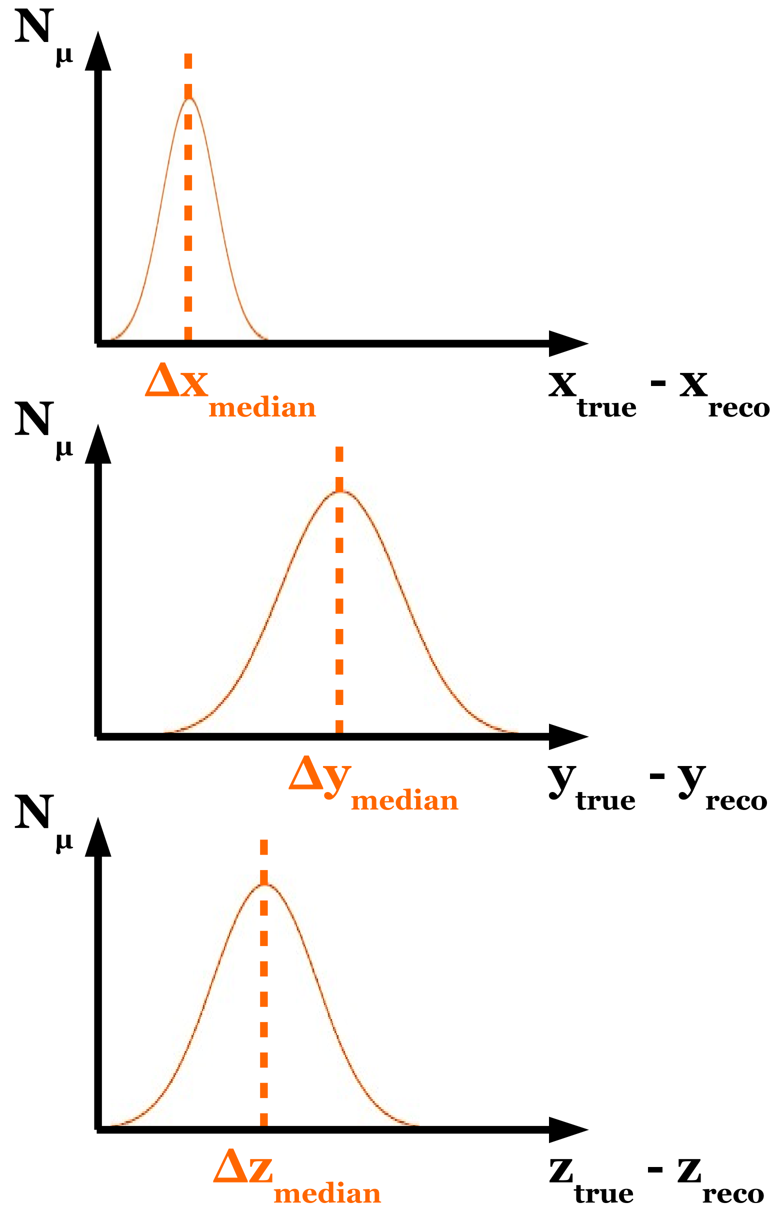


SCT "μ" Step: with MCS

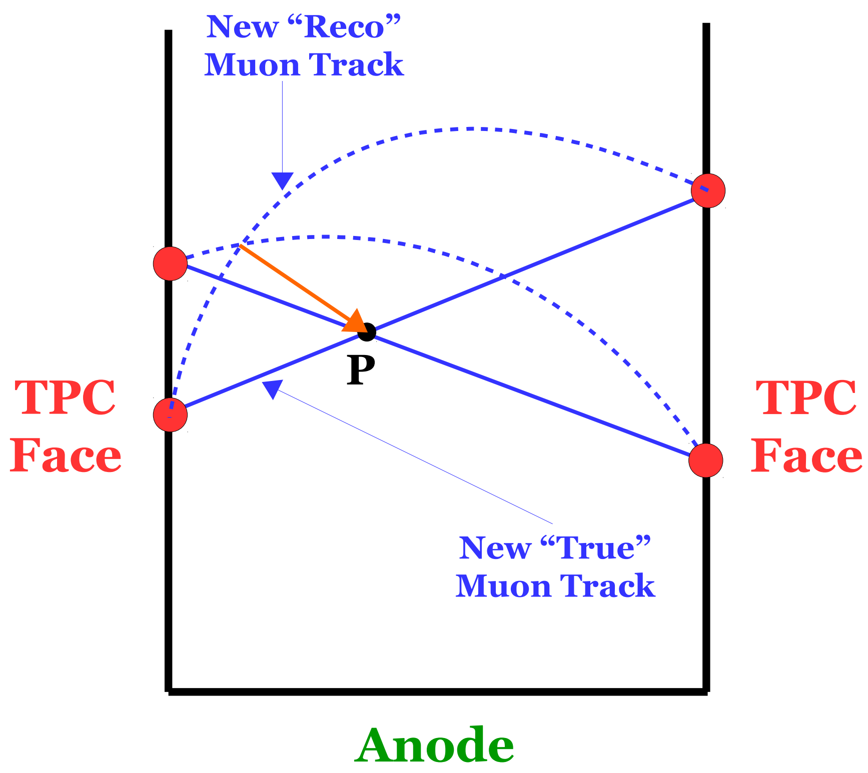


Correction to Point P:

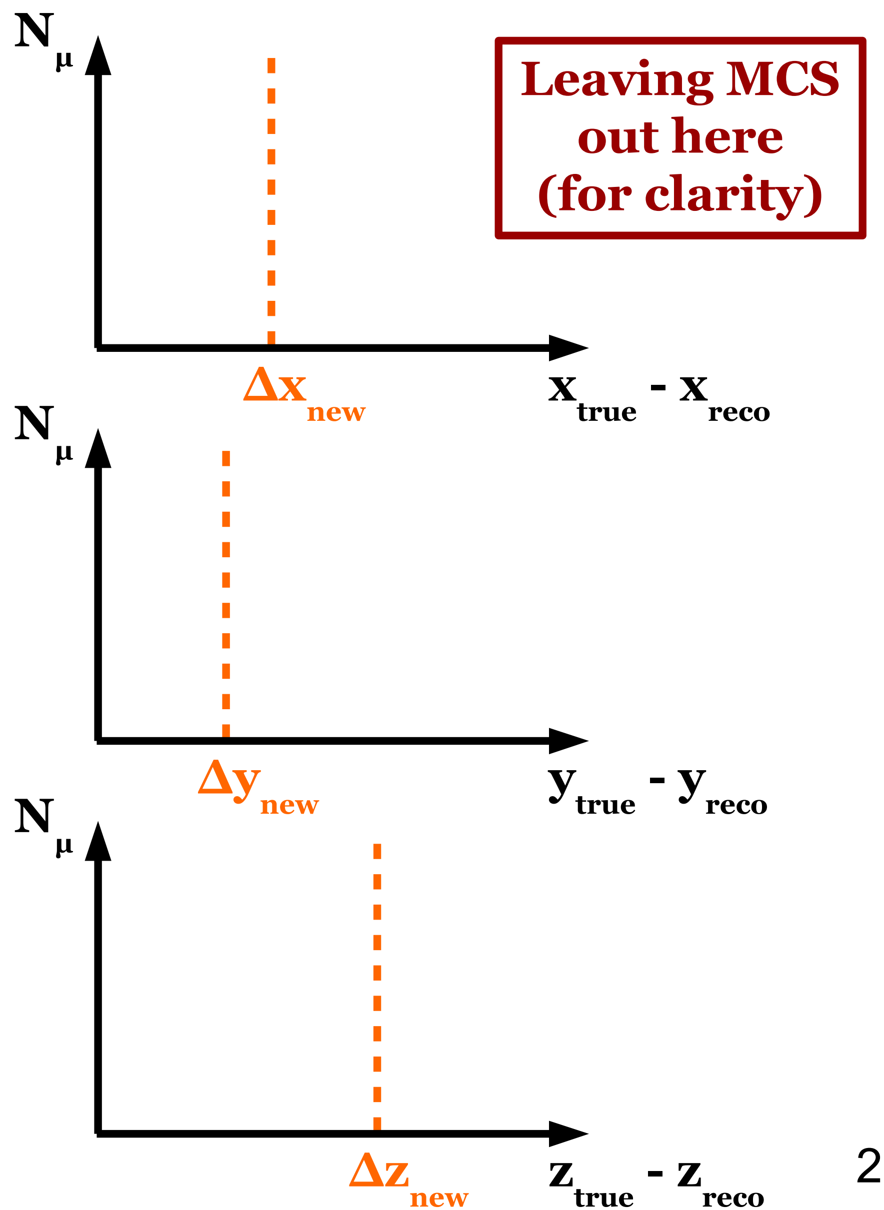
$\{\Delta x_{median}, \Delta y_{median}, \Delta z_{median}\}$

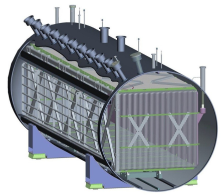


Another SCT "μ" Step ("X"-like)



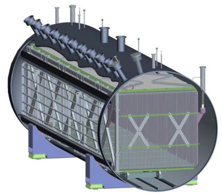
Update Correction to Point P





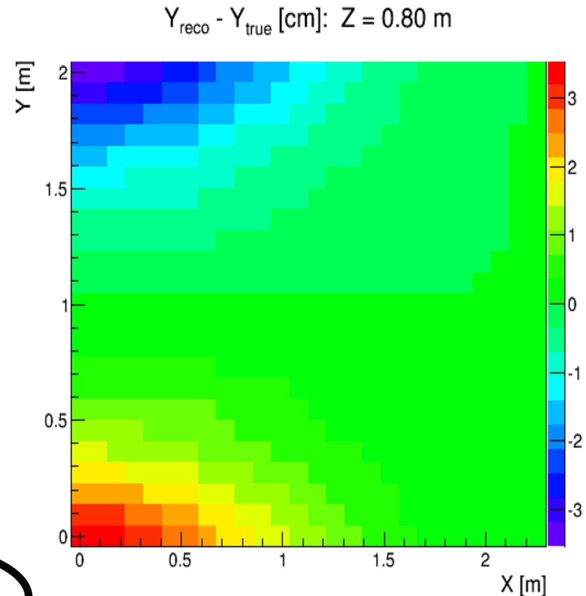
Summary/Plans

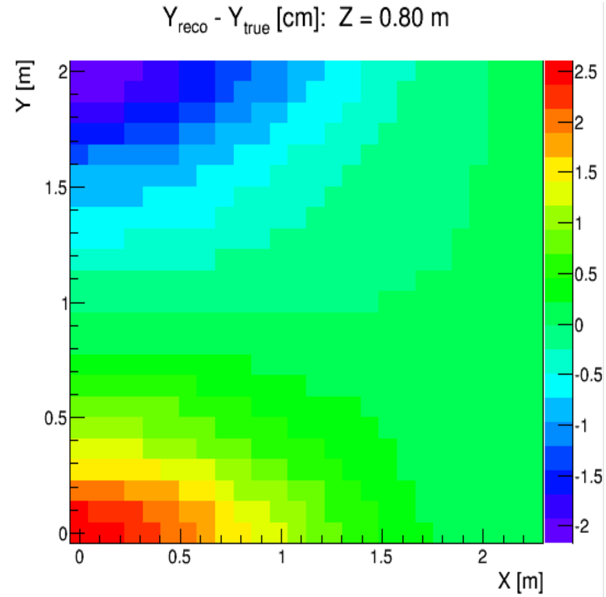
- **SpaCE** – use to study space charge effect at MicroBooNE
  - Understand simple problems first
  - Stand-alone C++ code with ROOT libraries
  - Can import into LArSoft for purposes of **simulation** and **calibration**
    - This effort has already begun!
    - Will be available for other experiments (e.g. 35-ton)
- Working with Erik Voirin to understand possible effects of **LAr flow** on space charge configuration – impacts calibration ideas
- Study **SCT (Space Charge Tomography)** calibration scheme
  - First using toy MC, then LArSoft simulation, then actual data



35-ton Sneak Peek!

E$_y$
Without
LAr Flow



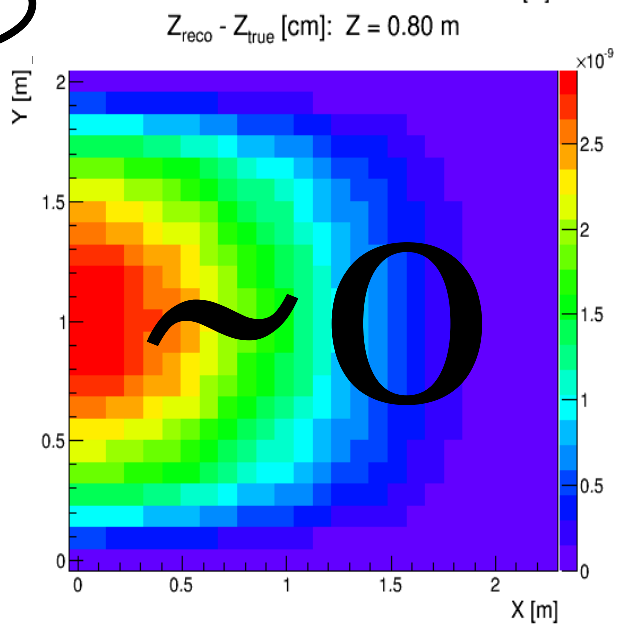


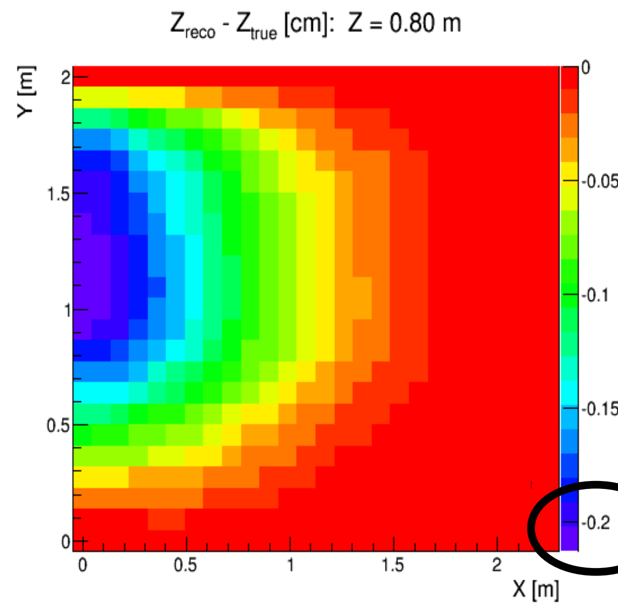
E$_y$
With
LAr Flow

Q map from E. Voirin

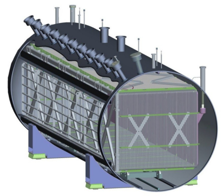
central z slice

E$_z$
Without
LAr Flow

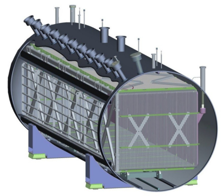




E$_z$
With
LAr Flow

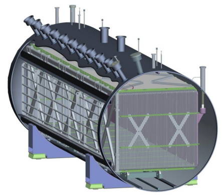


BACKUP SLIDES



Relevant Numbers

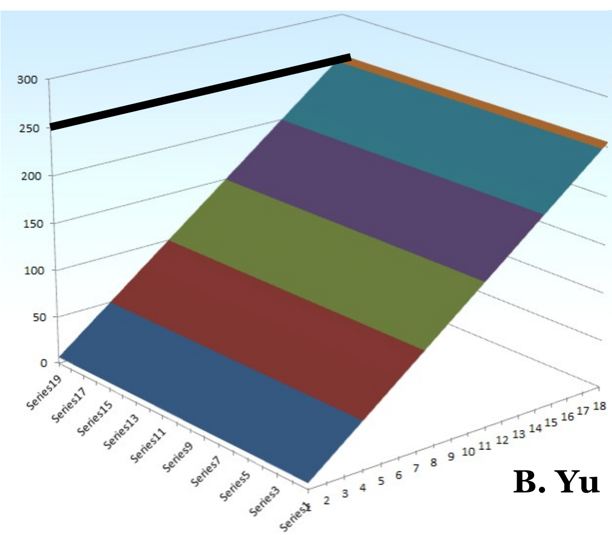
- Nominal electron drift velocity: **1.6 mm/μs**
- Ion drift velocity: **8 mm/s**
- Cosmic muon flux:
  - Vertical: **200/m²/s**
  - Horizontal: **60/m²/s**
- Max ion charge density in LAr: **90 nC/m³**
- Expected modification to magnitude of E field (compared to nominal drift E field of 500 V/cm):
  - Typical: **±3%**
  - Maximal: **±6%**
- Worst-case effects on reconstructed electron position:
  - Drift direction: **1.5 cm**
  - Lateral directions: **8 cm**



Complications

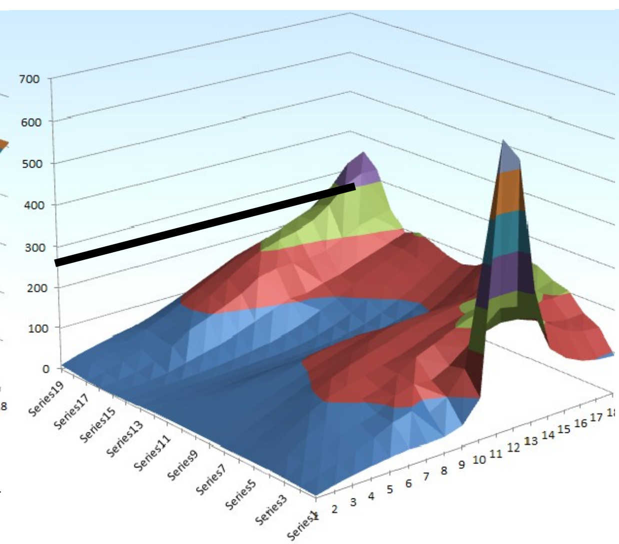
- Not accounting for non-uniform charge deposition rate in detector → significant modification?
- Flow of liquid argon → likely significant effect!
  - Previous flow studies in 2D… differences in 3D?
  - Time dependencies?

No Flow

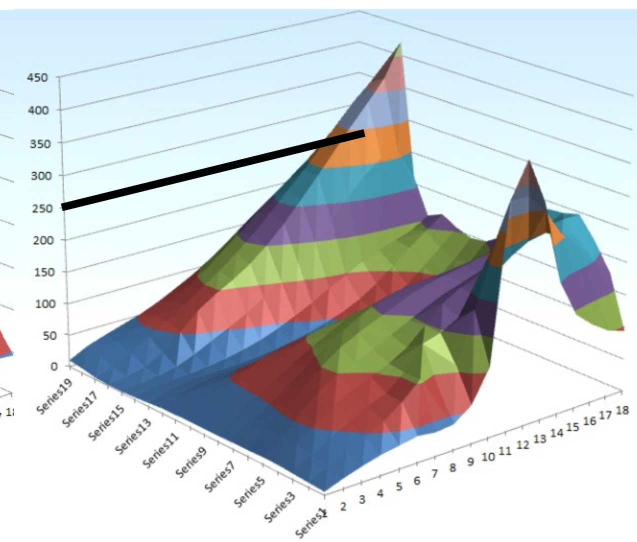


B. Yu

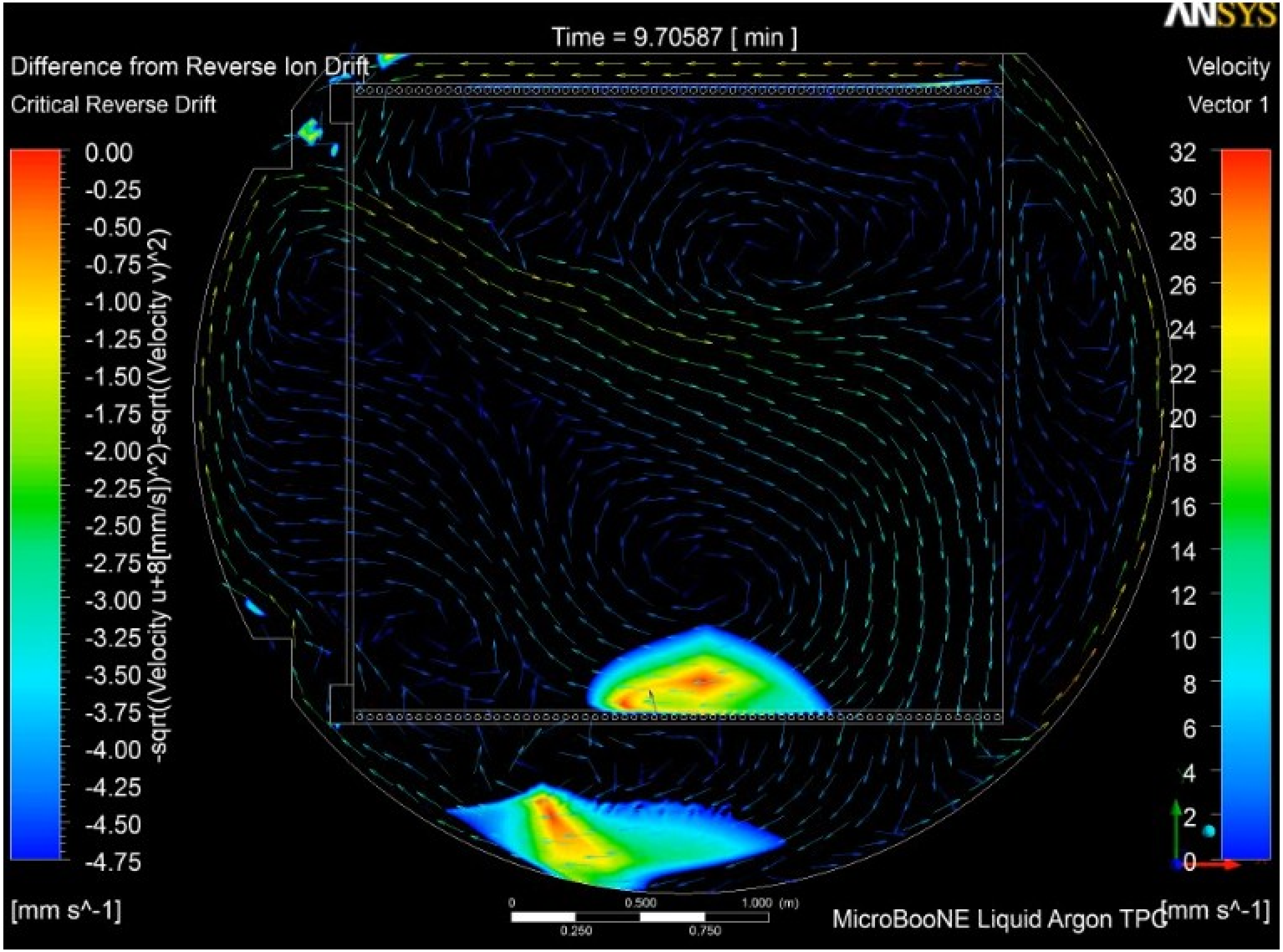
Flow w/o Turbulence



Flow w/ Turbulence



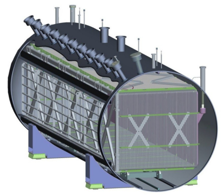
Liquid Argon Flow



B. Yu

SpaCE Performance

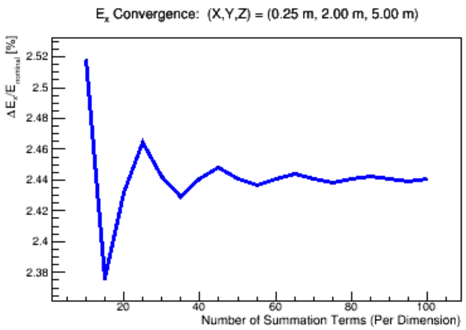
- Faster ray-tracing time
  - Was **~5 minutes** per cosmic event (10 random tracks)
  - Now **~10 seconds** per cosmic event
  - Can get ~10,000 events in one day of running on **one** machine
    - Use ensemble of events to test calibrations that make use of cosmic muons
    - Can use parametric methods to speed studies up significantly
- Improved E field interpolation between grid points
  - Used 5 layers of grid points outside boundaries
  - Points not physical (not inside volume) but help smoothing of solution near edges
  - Boundaries vastly improved, regions near cathode still a minor issue (~10% discrepancy w.r.t. correction to nominal drift field)

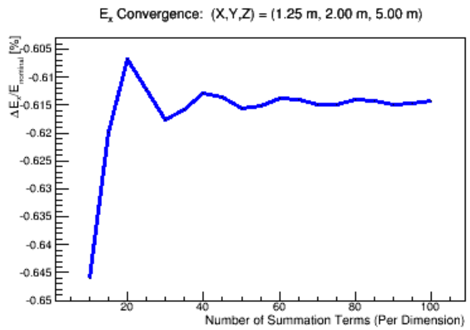


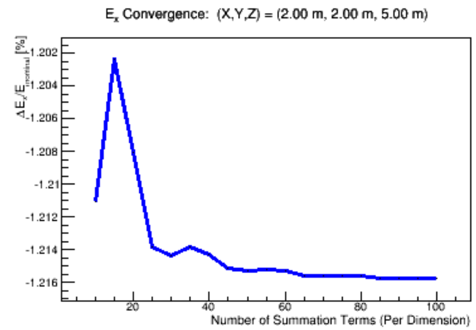
E Field Calc. Convergence

<u>Example</u>: E_x Convergence in x-y Plane (z = 5 m)

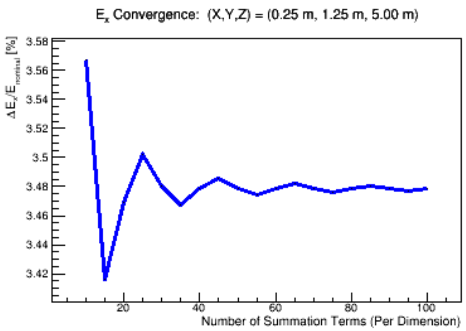
y = 2 m

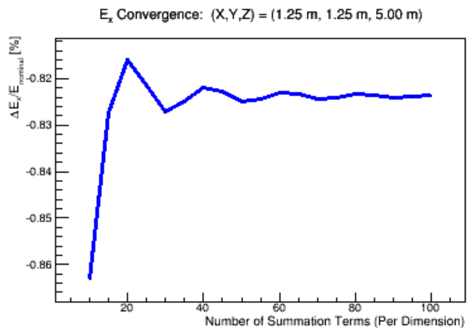


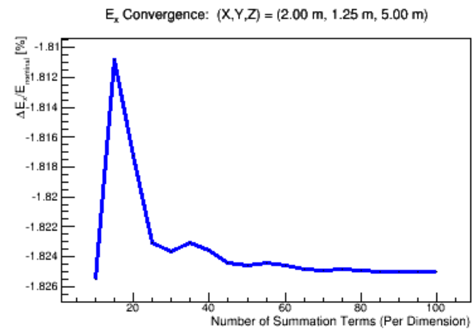




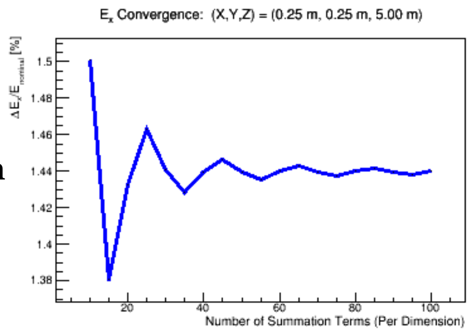
y = 1.25 m

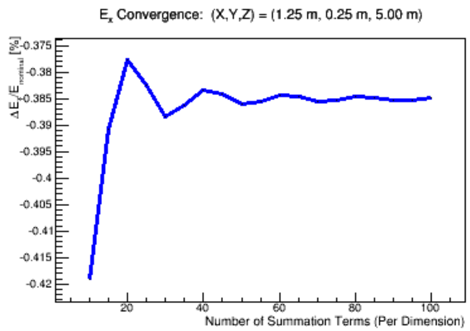


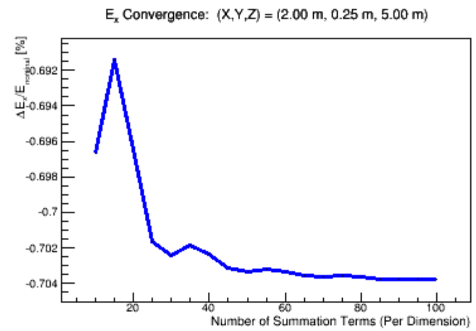




y = 0.25 m

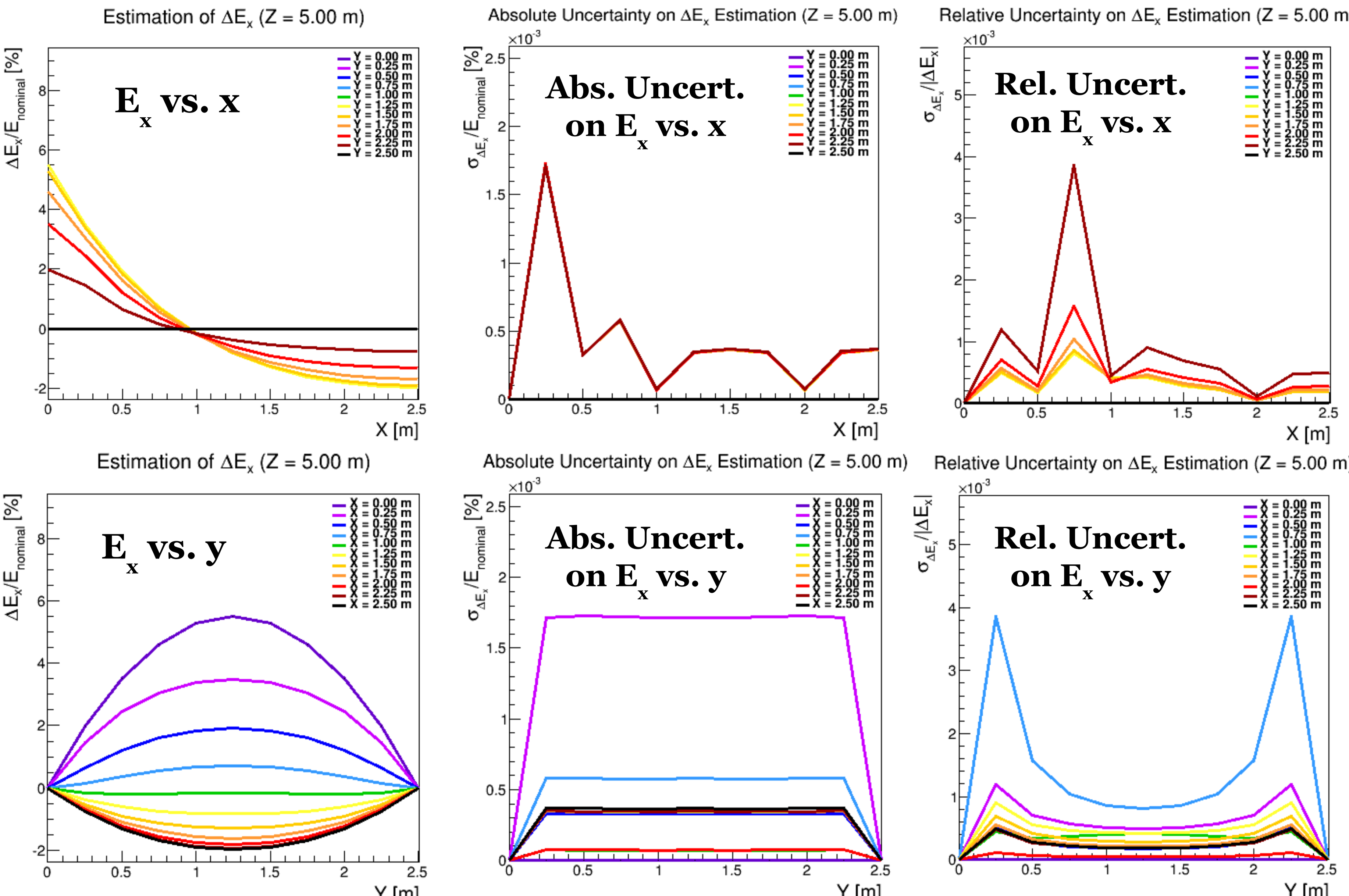






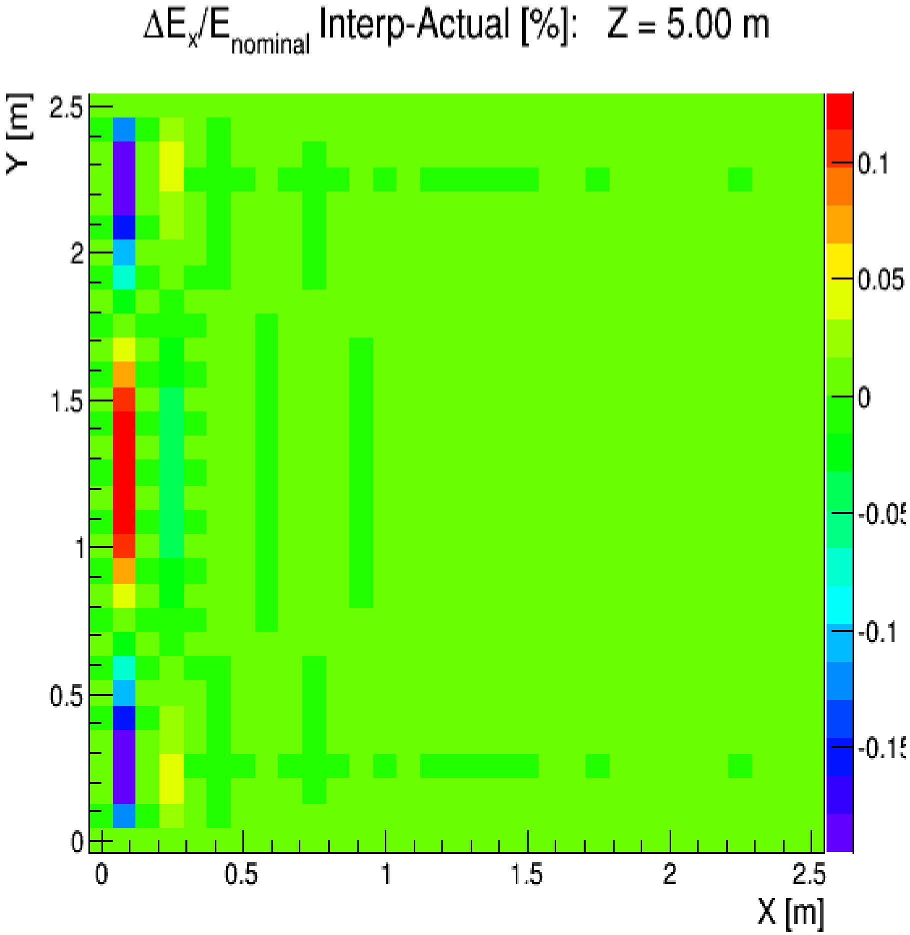
x = 0.25 m | **x = 1.25 m** | **x = 2 m**

E Field Calc. Uncertainty

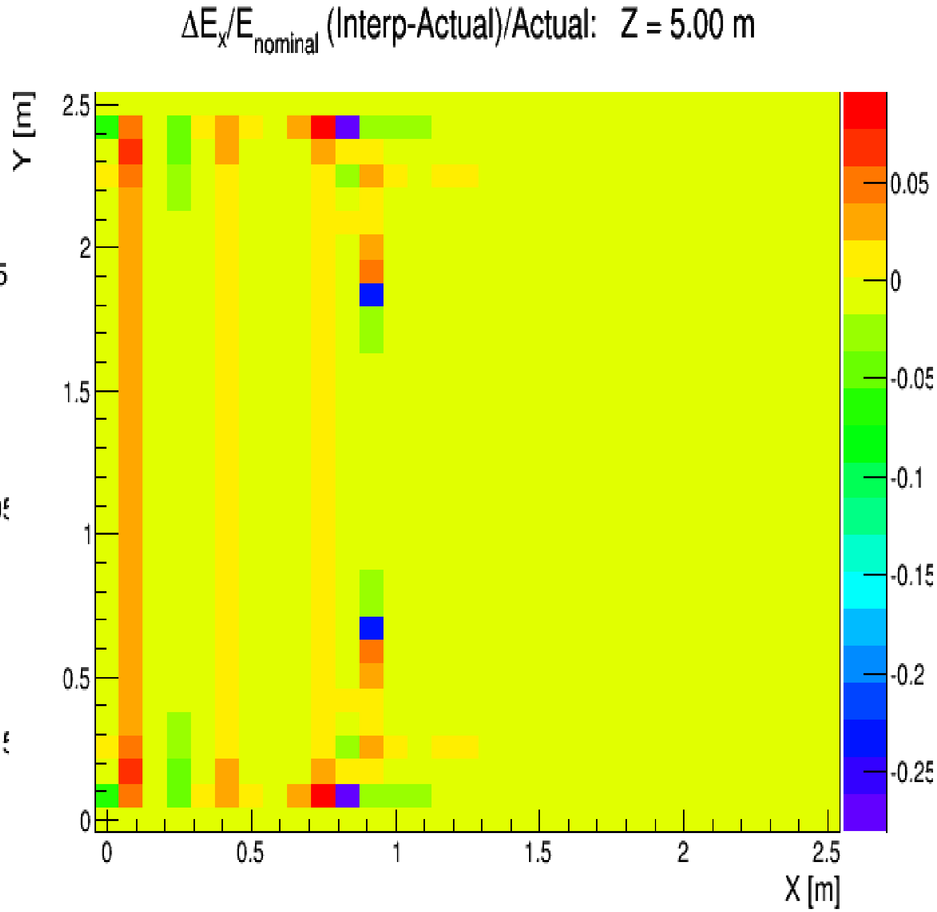


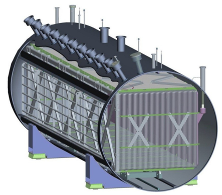
E Field Interp. Uncert.

E_x Difference

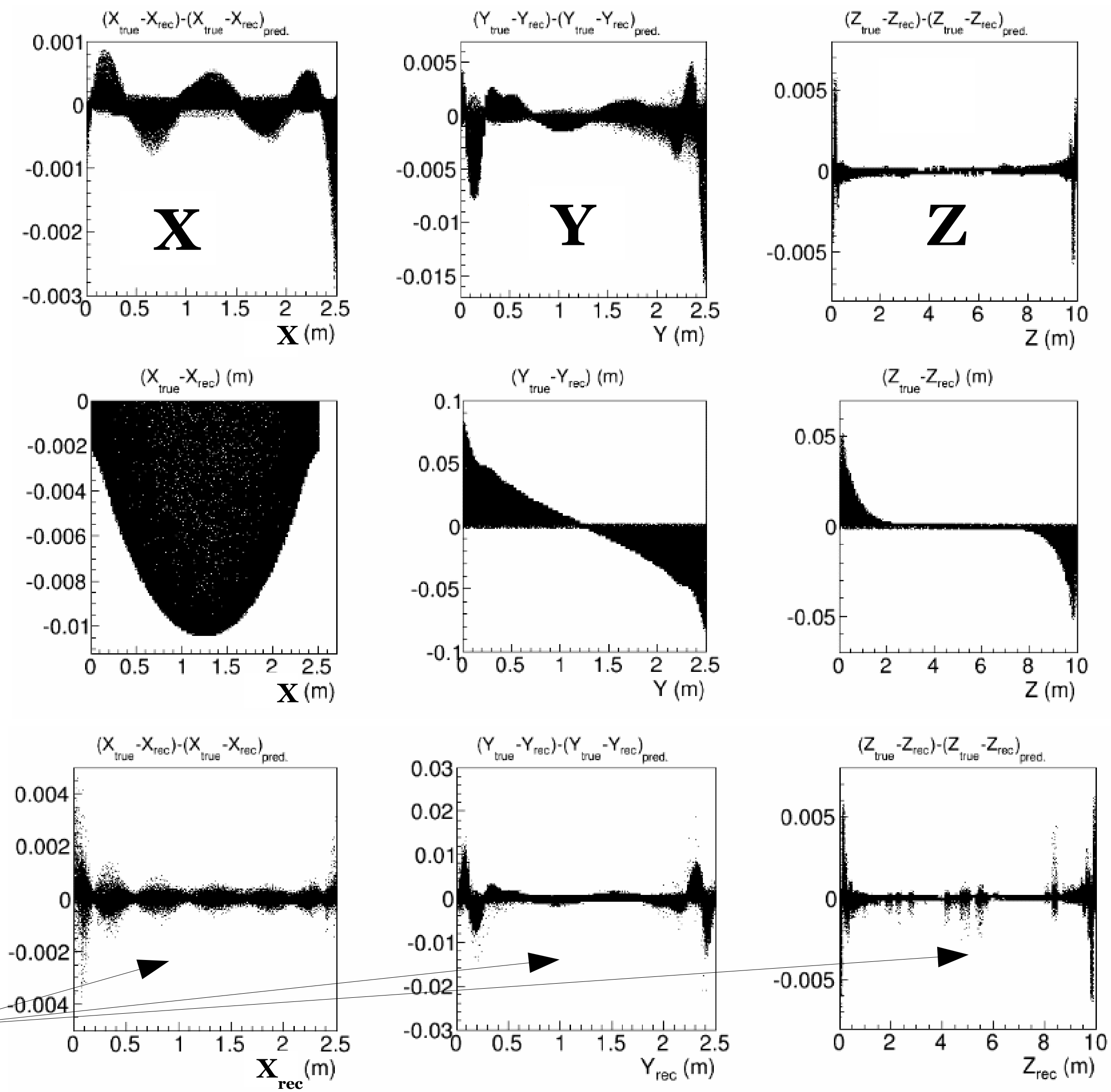


E_x Ratio





Simulation: Parametric Rep.



Residuals of Forward Transportation (Uncert. in Simulation of Effect)

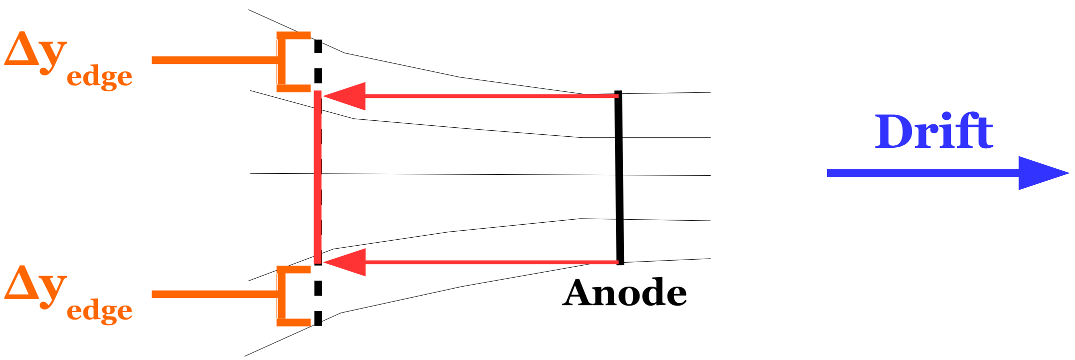
Impact of Space Charge Effect (Reconstruction Bias)

Residuals of Backward Transportation (Post-bias-correction Uncert. for Perfect Calibration)

Reality: these will be larger!

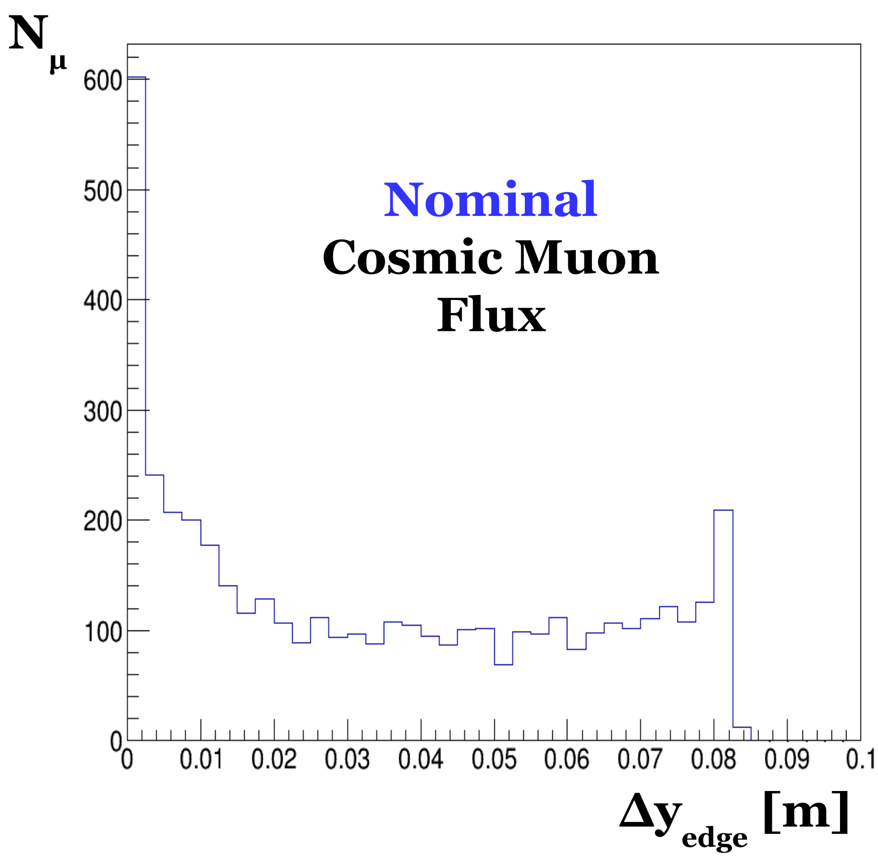
Smoking-gun Test for SCE

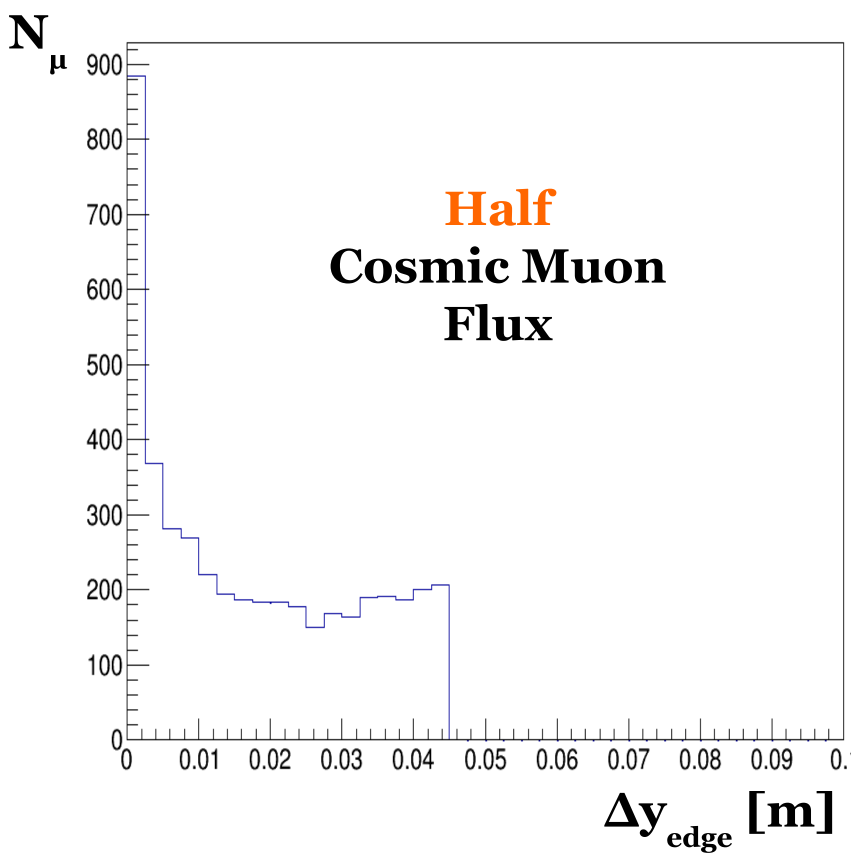
- Can use cosmic muon tracks for calibration
  - Possibly sample smaller time scales more relevant for a particular neutrino-crossing time slice
  - Minimally: data-driven cross-check against laser system calibration
- **Smoking-gun test**: see lateral charge displacement at track ends of non-contained cosmic muons → space charge effect!
  - No timing offset at transverse detector faces (no E_x distortions)
  - Most obvious feature of space charge effect

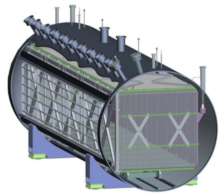


Cosmics: Dist. from Edge

- Very clear qualitative signs of effect in this distribution
- Sensitivity to rate of cosmic muon flux
    - Sharp cut-off at maximal distortion

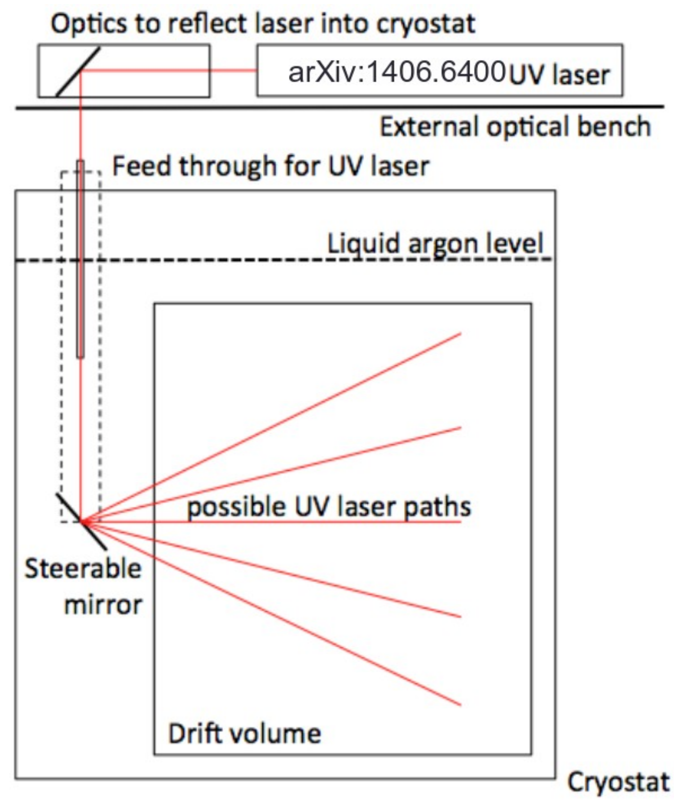


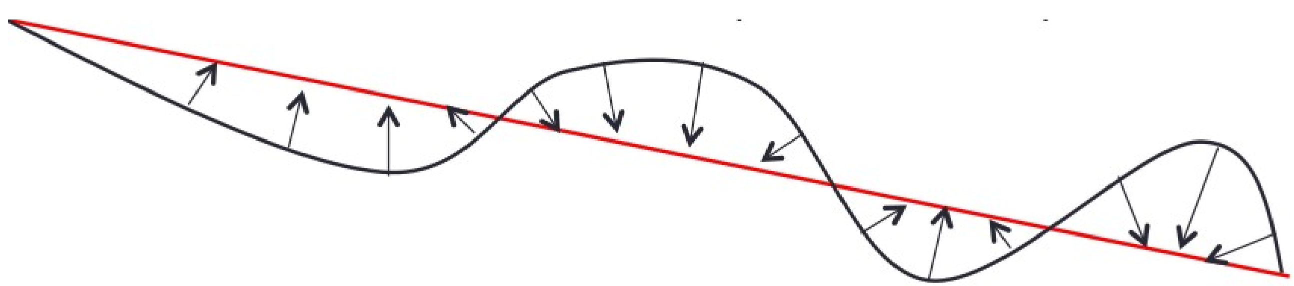




Laser System

- Can use laser system for calibrations, but:
  - Only once per day
  - Limited set of laser paths
  - Ambiguity of correction direction for reconstructed ionization electron clusters
- Intersection of two laser beams would remove ambiguity
  - Use to seed correction algorithms
- Working with Christoph to help evaluate calibration methods

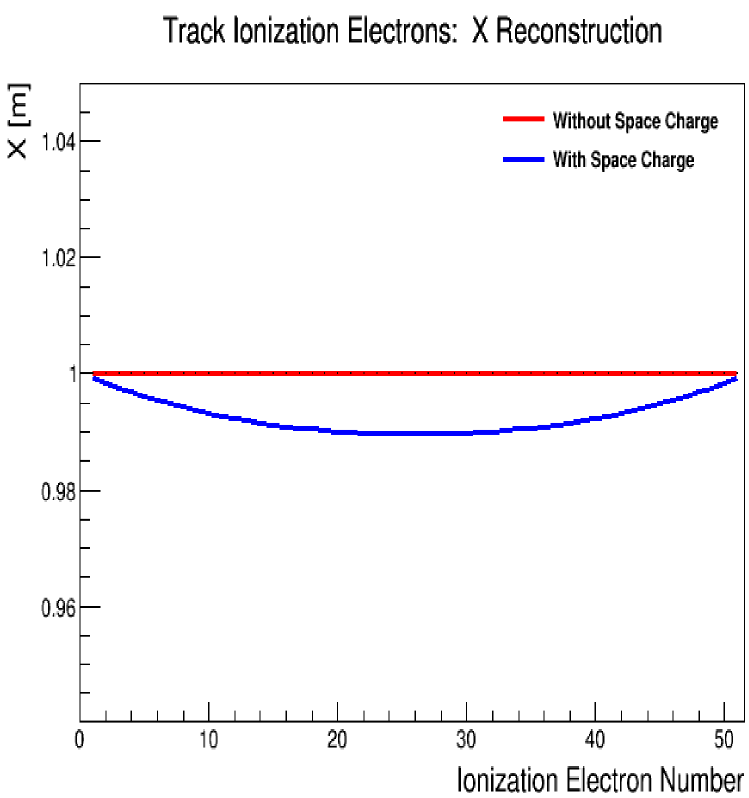




MCS Simulation Example

X

No MCS



X

With MCS